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The Performance Gap in New Construction: Evaluation of UK Passivhaus Dwellings

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Declaration I am the author of this thesis, and the work described therein was carried out by myself personally, with the exceptions highlighted in the declaration of authorship preceding each publication

Abstract

It is becoming clear that many new homes are using more energy in-use and overheating to a greater extent than predicted by building models. This performance gap has implications for the credibility of the construction industry and leaves building owners bearing the cost. In addition, as homes become more energy efficient to reduce carbon emissions, the existence of the performance gap means national underreporting of greenhouse gas emissions from this sector, which impacts on managing climate change. There is also emerging evidence linking increased dwelling energy efficiency with increased overheating risk - with the causes uncertain.

The direction of new housing in the UK is currently out for consultation through the Future Homes Standard. This suggests that a large-scale evaluation of the measured performance of existing low energy building standards would be timely, to help inform both future housing policy and our understanding of the performance gap.

Hence, this thesis aims to evaluate the key metrics of space heating demand and internal temperature data from UK homes, certified to the widely adopted low-energy Passivhaus standard, looking for evidence of the performance gap in both energy use and overheating risk. Since a performance gap can only be evaluated through access to both the predicted and observed parts of the problem, due consideration is first given to obtaining reliable predictions and then obtaining large-scale observed data for both winter and summer. The research is centred around three key questions.

Can a simplified method for temperature and weather normalisation be developed? There are many reasons for differences between design and measured energy use. In steady state building models such as Passive House Planning Package (PHPP), used to design and certify Passivhaus buildings, and the UK Standard Assessment Procedure (SAP), design internal temperatures are fixed. In reality, there will be differences between these design assumptions and user preferences. Being able to account for this, especially in low-energy homes, is essential, but is complicated by the fact that the original assessment may not be accessible at the time of a post-occupancy evaluation. Hence, a method was developed for these two routinely used building assessment models, to allow for temperature, solar and internal gains corrections to be made, without access to the original assessment. The results showed that measured internal temperature has the greatest impact on space heating variation, compared to solar and internal gains, thus reducing the level of data collection needed on-site. Applying these findings allow internal temperature normalisation to be undertaken more frequently, to eliminate this element of the energy performance gap.

Is there a performance gap between internal temperatures and the overheating risk methodology in PHPP and how does this prediction compare to other methods? Dry bulb internal temperature data from 82 certified Passivhaus homes, with different tenures, from varying locations, was analysed using Passivhaus (fixed temperatures) and CIBSE TM59 (adaptive comfort) overheating risk methodologies. Results showed that while most homes met both standards, the single zone approach of Passivhaus had the potential to mask overheating risk in individual rooms, especially bedrooms, where high internal temperature impacts more on health and comfort. TM59 focuses on the summer months only and could miss overheating outside of this season. When applied to bedrooms only, comparison of the two standards showed similar results, especially when using Passivhaus good practice levels (-50% of the maximum allowable hours). This showed that either assessment could be applied to measure overheating risk in domestic homes.

How do Passivhaus dwellings in the UK perform once occupied, compared to the space heating prediction in design models (PHPP)? Space heating data was collected from 97 certified Passivhaus homes (this sample included the 82 homes analysed for overheating risk). Using three different collection methods (i) heat metering(ii) monthly meter readings and (iii) bi-annual meter readings, which reflected the levels of data available, the results showed no evidence of the energy performance gap for space heating. In fact, despite using a cautious approach, which overestimated rather than underestimated the heating demand, on average the homes used less heating than predicted. This negative gap further increased when the normalisation technique developed in research question one was applied. Analysis of the data collection methods showed that minimal monitoring can yield useful results for estimating space heating demand.

This thesis demonstrates that homes certified to the Passivhaus standard do not show the energy performance gap, contrary to the findings in homes constructed to other standards. In addition, overheating risk can be managed using both the Passivhaus method and CIBSE TM59. These findings are then discussed in the context of the Future Homes Standard and the benefit of adopting a verified design is considered.

Outputs of Research

The research undertaken to complete this thesis has been published in peer reviewed journals and presented at national and international conferences. The data has been used by the Passive House Trust to promote the Passivhaus standard in the UK. The data is available in publicly accessible data bases.

Three papers (two published, one submitted) are incorporated into this thesis and are shown in Table 1 below.

Paper	**Publication details**	**Location in thesis**
Normalising domestic space heating demand using post hoc models	Building Services Engineering Research and Technology, 40(3), 340–359 Published 18 December 2018 https://doi.org/10.1177/0143624418816431	Chapter 2
Overheating risk in Passivhaus dwellings	Building Services Engineering Research and Technology, 40(4), 446–469.Published 08 April 2019 https://doi.org/10.1177/0143624419842006	Chapter 3
UK Passivhaus and the energy performance gap	Energy and Buildings Volume 224, 110240.Published 1 October 2020 https://doi.org/10.1016/j.enbuild.2020.110240	Chapter 4

Table 1. Summary of peer reviewed papers

Conferences

Mitchell R and Natarajan S. 'Proving Passivhaus: Post occupancy evaluation of certified Passivhaus homes in the UK' UKPH 2016 conference London UK

Mitchell R and Natarajan S. Proving Passivhaus: Post occupancy evaluation UK Passivhaus homes. 21st International Passivhaus conference Vienna 2017.

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List of Abbreviations

CCC	Climate Change Committee
EPBD	Energy Performance in Buildings Directive
BPE	Building Performance Evaluation
EPC	Energy Performance Certificate
EPG	Energy Performance Gap
FHS	Future Home Standard
GHG	Greenhouse Gas
MVHR	Mechanical Ventilation with Heat Recovery
Non-PH	Not built to Passivhaus
PH	Passivhaus
PHPP	Passive House Planning Package
POE	Post Occupancy Evaluation
PV	Photovoltaics
SAP	Standard Assessment Procedure
ZCH	Zero Carbon Hub

Chapter 1 Introduction

UK residential buildings are responsible for approximately 20% of total greenhouse gas emissions (GHG), and this proportion has been more or less static since 2014, with a small increase in 2017 (BEIS, 2020a). Against this backdrop of stalled reductions, there is mounting evidence that buildings are not performing in-use as expected. Many homes use much more energy than predicted in the Standard Assessment Procedure (SAP) assessment or shown in the Energy Performance Certificate (EPC) (ZCH, 2014a, de Wilde, 2014, Wingfield et al., 2008, Johnston et al., 2014). This impacts not just on energy bills and the risk of fuel poverty, but leads to an underestimation of the contribution buildings are making to GHG emission, and undermines carbon reduction strategies (ZCH, 2014b).

In addition, homes need to be adapted for future climate change. It is estimated that 20% of all domestic buildings overheat in our current summers (BRE, 2013a). As homes become highly insulated and air tight, there is a concern that these dwellings are more at risk from overheating (ZCH, 2015a, McGill et al., 2017b), though the evidence here is mixed (Fosas et al., 2018). However, what is clear is that some homes are overheating and this can only increase as temperatures rise (BRE, 2013a). High internal temperatures not only affect thermal comfort, they affect health. Heat-related deaths in the UK are predicted to triple by the 2050s to 7,000 per year, with older people the most at risk.(EAC, 2018).

Furthermore, there is an unmet demand for housing in the UK, and to satisfy this there is an ambitious house building programme proposed, with up to 1.5 million new homes to be constructed by 2025 (HM Treasury, 2017).

These scenarios of energy and carbon emissions reduction targets, the energy performance gap (EPG) overheating risk and a large-scale building programme, create three distinct challenges to the housebuilding industry.

1. All new homes need to be ultra-low energy.
2. All new homes need to perform as expected in terms of regulated energy use and subsequent carbon emissions to ensure national reduction targets are actually met.
3. All new homes should be thermally comfortable, not overheat in the current climate and be resilient to future temperature increases.

It is recognised that the EPG can also be linked to unregulated energy use and climate resilience include other extreme weather events such as storms and floods, but this is beyond the limits of this thesis. These three themes form the basis of this thesis and are addressed in chapters 2, 3 and 4.

1.1 Broader picture

In 2019, the UK passed legislation to achieve net zero carbon by 2050 (Parliament : House of Commons, 2019). The 2050 climate objectives cannot be achieved without the decarbonisation of both new build and existing homes, with predicted emissions needing to fall from the whole building stock by 24% from 1990 levels (CCC, 2019). Therefore, current policies to reduce GHG in buildings are not producing the carbon reductions needed, and homes being built now need to be very low energy, with ultra-high levels of building fabric (CCC, 2019).

1.2 The Passivhaus Standard

The Passivhaus standard is a widely used and internationally recognised low energy standard. To date 60,000 units have been certified (iPHA, 2020). Homes built to the Passivhaus standard are designed to need very little energy for heating and cooling and provide good indoor air quality and comfort (Feist W, 2001). The principles, developed by the Passive House Institute in Germany require attention to detail in the design, construction and commissioning phases (PHT, 2012).

The main features of a Passivhaus are, high levels of insulation and airtightness, triple glazed windows, mechanical ventilation with heat recovery (MVHR), detailing of thermal bridge junctions and an assessment for overheating risk. In addition to the design stage assessment, there is a quality assurance process for site management and commissioning post construction, to ensure that the building performs as intended, to address the EPG issue. A summary of the Passivhaus standard for European climates (PHI, 2015b) is given in Table 2. This reflects the change in the primary energy maximum to 135 $kWhm^2a^{-1}$ from 120 $kWhm^2a^{-1}$ in previous versions.

	Limiting standard
Space heating demand	≤15 kWh m^2a^{-1}
Heat load	≤10 W m^2a^{-1}
Primary energy demand	≤135 $kWhm^2a^{-1}$
Building Fabric	**Limiting standard**
Floor/Walls/Roof	≤0.15 Wm^2K^{-1}
Windows and doors	≤0.8 Wm^2K^{-1}
Air permeability	≤0.6ach_{n50}
Thermal bridges	Zero
Overheating	≤10% occupied hours over 25^{o}C internal temperature (modelled)

Table 2. Summary of the main elements of the Passivhaus standard (current version V9.6)

1.2.1 Passive House Planning Package

Designing and demonstrating compliance with the Passivhaus standard is achieved using Passive House Planning Package (PHPP) which was developed by the Passive House Institute (PHI) in 1988 and is based on EN 832 (ISO 13 790). PHPP comprises of a series of interconnected spreadsheets representing steady state monthly heat flow and is used to calculate the annual heat balance, final energy demand and overheating risk. It has been calibrated with dynamic simulation models (DYNBIL) and verified against measured consumption data (PHI, 2007, Feist W, 2001).

Each certified Passivhaus goes through a quality assurance process, through a detailed review of the design and construction, including evidence from site, by an experienced independent certifier. This is to ensure that the building will perform as intended (Feist et al., 2015a).

1.2.2 The Passivhaus Standard in the UK

The first UK Passivhaus (PH) was certified in 2009, and since then the numbers of certified buildings has increased year on year (PHT, 2018b). In 2012, when only 165 certified buildings had been either constructed or in progress, Passivhaus was considered a challenging standard, with complexity and cost barriers to is wide scale adoption in the UK (NHBC, 2012a). However, this is changing. To date, it is estimated that at least 1255 units have now been certified, with a larger number under development (PHT, 2020a). Passivhaus buildings are designed to deliver a 75% reduction on space heating compared to standard building practice in the UK and could be used as the vehicle to deliver the 80% reduction in carbon emission required nationally by government (PHT, 2020b).

1.3 Reducing energy and carbon emissions in new dwellings

Revisions to Approved Document Part L1A of Building Regulations *Conservation of fuel and power in new dwellings* are the route to reducing energy and carbon emissions in new homes in the UK (Garmston and Pan, 2013). Consultation is currently underway to both update Part L1A and the Standard Assessment Procedure (SAP), the UK government's energy demand assessment methodology for domestic buildings (BRE, 2013c). Within this consultation, the direction of travel for new construction is given in the Future Homes Standard (FHS), proposed for 2020. The FHS aims to reduce carbon emissions from new dwellings by 75-80% compared to current regulations and combines improved building fabric and low carbon heating systems. As the national grid continues to decarbonise, natural gas as the main source of heat energy, will be replaced by heat pumps and heat networks.

The EPG is also addressed through measures to strengthen compliance and build quality at the construction phase. Site inspections, including site photographs and checks on insulation and thermal bridge installation are proposed, and a more vigorous air testing regime. (MHCLG, 2019).

The FHS proposes four performance metrics: (i) Primary energy target which aligns with the EU Energy Performance in Building Directive (EPBD) will be the principal metric. With (ii) CO_2 emissions targets (iii) Householder affordability rating and (iv) Minimum standard for building fabric and fixed building services as secondary metrics.

Though the FHS is yet to be fully defined, two options have been suggested. These propose to reduce maximum U values for opaque surfaces, windows and doors, some of which match or exceed the Passivhaus standard (MHCLG, 2019). However, both options allow for natural ventilation as opposed to the Passivhaus limitation of very low airtightness and MVHR (see Table 3 for a comparison of the PH standard and the two proposed FHS options).

	Passivhaus standard	**Future Homes standard option 1**	**Future Homes standard option 2**
Building Fabric	**Limiting standards**		
External wall	≤0.15 Wm^2K^{-1}	≤0.15 Wm^2K^{-1}	≤0.18 Wm^2K^{-1}
Roof	≤0.15 Wm^2K^{-1}	≤0.11 Wm^2K^{-1}	≤0.11 Wm^2K^{-1}
Floor	≤0.15 Wm^2K^{-1}	≤0.11 Wm^2K^{-1}	≤0.13 Wm^2K^{-1}
Windows	≤0.8 Wm^2K^{-1}	≤0.8 Wm^2K^{-1}	≤1.2 Wm^2K^{-1}
Door	≤0.8 Wm^2K^{-1}	≤1.0 Wm^2K^{-1}	≤1.0 Wm^2K^{-1}

Air permeability	≤0.6ach$_{n50}$	5m^3/hm^{-2}@50Pa	5m^3/hm^{-2}@50Pa
Thermal bridges	Zero	Improved thermal bridge details compared to current standards	Improved but less so than Option 1, thermal bridge details compared to current standards
Overheating	≤10% occupied hours over 25^{o}C (internal temperature)	New requirements to be agreed	New requirements to be agreed

Table 3. Comparison of PH standard with FHS Options 1 and 2

The Climate Change Committee (CCC) have also described future UK low carbon homes. The main features of this are similar to the FHS (low U values and triple glazing), but also includes high levels of airtightness with MVHR (CCC, 2019). With a space heating demand of 15-20 kWhm^{2}a^{-1}, this proposed housing design aligns more closely to the PH standard than FHS.

Therefore, in the UK, potentially Passivhaus is moving from a small scale, niche standard, to the principles being incorporated the mainstream, not only for the design elements of the building envelope, but with better quality control on-site to address the EPG.

However, as stated above, the numbers of certified PH dwellings constructed in the UK are low, compared to non-PH new homes. If the PH standard or principles are to be adopted, there needs to be a wide scale evaluation of the delivery of the standard in the UK to date, to ensure the EPG is not present. Without this check, if the standard is upscaled, elements of the EPG could emerge, which would undermine its expansion as either, the adopted low energy building standard, or elements of it being incorporated into new building codes.

Chapters 3 and 4 address this issue, by collecting data from a large number (97) of certified Passivhaus homes, from a range of sites (13), both small and large scale with different tenure types. This is a comprehensive gathering of data, to allow an overview of the performance of the standard for the three key issues, (1) Ultra low energy homes (2) EPG and (3) Overheating risk.

1.4 The Energy Performance Gap

It is well documented that both new and existing homes are using more energy than expected (Wingfield et al., 2008, Wingfield et al., 2011, ZCH, 2014a, Johnston et al., 2014, Gupta et al., 2019). Within the literature, three main areas have been identified which contribute to the EPG (i) Building models, (ii) Construction, (iii) User behaviour.

1.4.1 Building modellers and tools

The assessment tool for showing compliance with Approved Document Part L1A of UK Building Regulations is the Standard Assessment Procedure (SAP) (BRE, 2013c). The accuracy of the output of any building model depends on the accuracy of the input. Inconsistencies in SAP data input were often found (Trinick et al., 2009, Wingfield et al., 2011, Gupta and Dantsiou, 2013, Grigg and Slater, 2004). Once these inputs were corrected, there was a greater alignment between design and in-use, meaning competency and training are critical (South, 2007, ZCH, 2014a).

Building modellers must understand how buildings work. There can be significant differences between modellers, on the hierarchy of inputs which affect space heating outputs (Imam et al., 2017). The consistency of thermal transmittance calculations (U values) and heat losses through junctions (Psi Values) were also questioned, and the need for qualified modellers in these disciplines identified (ZCH, 2014a).

Assumptions made within the building model may not be accurate. For example space heating prediction of 405 homes were found to be inconsistent in 60% of assessments, which are attributed to simplifications within the model, assumptions about user behaviour and different localised weather conditions (Hughes et al., 2016)

As building codes tighten, the calculation methods within building models need to remain robust. Some assumptions within SAP are not consistent with low energy design and can result in an underestimation of heating demand and a greater sensitivity to small changes in data (NHBC, 2012b). Testing the validity of SAP against a statistically significant sample of stock has also been questioned, especially in low energy buildings (Kelly et al., 2012). The ZCH also recognised there was limited as- built test data used in SAP calculations, and that whilst SAP was a generally a robust tool, the modelling of thermal by-pass and the interrelation of different building services systems were a possible weakness (ZCH, 2014a).

SAP is also used to assess summer overheating risk, to determine compliance with this section of Approved Document Part L1A. However, it is not considered adequate to undertake design modelling for overheating strategies (AECOM, 2012a). The NHBC also raised concerns about the ability of SAP to model overheating, especially the impact of complex factors such as thermal mass and night time ventilation (NHBC, 2012c).

Therefore, as homes become more energy efficient, SAP in its current form may be less useful as an assessment tool for both energy performance and overheating risk. In addition using SAP as a compliance tool which only takes into account design performance and not as-built performance is ineffective, and will not address EPG issues (ZCH, 2010b, Gorse et al., 2013).

1.4.2 Construction

Many elements of the construction and commissioning phase contribute to the EPG. These include: liaison and communication between parties, product substitution, poor installation and integration of materials and services, poor commissioning and testing, lack of team knowledge and skills, and limited quality assurance on-site (Cox, 2006, Wingfield et al., 2011, Bell et al., 2010, ZCH, 2014a, South, 2007, Gupta and Dantsiou, 2013). The research concluded there was a need to rethink of the whole construction process, including the interrelationship of different building regulations, the design process and modelling, training and knowledge, and the lack of performance monitoring and testing. To complicate matters more, many of the construction problems are hidden behind the final finish (South, 2007). Poor construction practice on-site, not only undermines thermal performance, but could increase the risk of damp, condensation and mould (GHA, 2012).

The percentage contribution of some construction elements and processes to the EPG have been calculated and are shown in Table 4 (Bell et al., 2010).

Construction element and/or process	Percentage contribution to the EPG
Poor detailing and installation on-site of non-repeating thermal bridges	25%
Additional repeating thermal bridges and the subsequent increase in U values	23%
Thermal bypass, especially at party walls	30%
Product substitution	21%

Table 4. Percentage contribution to the EPG of construction elements and processes Bell et al 2010

As energy performance standards increase, so does the need for good site practice and quality control. The tolerances to defects in the continuity of insulation, air permeability and building services become less, and have a greater impact on the EPG (ARUP, 2012). Therefore, as building fabric improvement increases with the implementation of the FHS or other low energy standards, this needs to be coupled with a greater focus on quality control on-site.

Passivhaus has an established quality control standard process imbedded in certification to reduce the EPG. The performance of this standard on space heating demand is reported in Chapter 3.

1.4.3 User behaviour

Building simulation models make assumptions to predict energy performance, one of which is target internal temperature. SAP 2012 assumes that homes are heated to 21°C in the living room and 18°-20°C in the remainder of the dwelling (BRE, 2013c). PHPP assumes an internal temperature of 20°C for typical domestic dwellings for certification purposes (Feist et al., 2015a). Heating to a higher internal temperature will lead to increased energy for space heating. The 'take back' factor or 'rebound' effect describes the phenomenon where occupants chose to heat their homes to higher internal temperatures than assumed for comfort reasons, which results in lower energy savings than expected (Milne and Boardman, 2000, Summerfield et al., 2007, Guerra Santin, 2013). This concept was originally applied to existing homes where average internal temperatures can be much lower (average 16.5°C) (Milne and Boardman, 2000). However some occupants of new homes are heating to higher than predicted temperatures, which are now on average 20.6°C, with a peak at 30°C (Palmer et al., 2016, Gupta and Kapsali, 2015).

1.4.4 Temperature normalisation

Temperature normalisation addresses two known causes of the EPG. (i) The accuracy of the building models and (ii) user behaviour. As discussed, if in-use internal temperatures are different to building model assumptions, the space heating demand prediction will change. An adjustment or normalisation can be made to take this difference into account and excluded from any EPG assessment. For non-PH homes, it is estimated that a 1°C increase in internal temperature translates to a 10% increase in space heating demand (Palmer et al., 2012).

POE data from PH homes show that internal temperatures tend to be higher than the assumption in PHPP (20°C), ranging between 21°C and 24°C (Schnieders, 2003b, Exner and Mahlknecht, 2012). In low energy buildings such as PH, the impact of increased internal temperature on space heating demand is greater than for non-PH buildings. For each 1°C temperature above 20°C, space heating consumption can rise by 12–15%. (Peper, 2017).

Therefore a Passivhaus home, with a 22°C winter internal temperature may have a space heating demand between 4 and 5 kWh m^2a^{-1} above planned consumption (Peper, 2017).

Therefore, when comparing predicted and observed demand, it is important to normalise to ensure a like for like comparison. A simple but accurate method would be to update the original building model to reflect the conditions in-use and to recalculate space heating demand. However, this method is hampered by lack of access to that model, especially post occupancy, and for large sites, this would rely on multiple updates. In chapter 2, a method is developed and tested to overcome this barrier and allows for temperature normalisation to be undertaken without access to the original building model. This method is then implemented in chapter 4, to allow more homes to be normalised.

1.5 Overheating risk

If the building modelling tools available are unable to reliably predict if a dwelling is at risk of overheating, then there is a performance gap between design prediction and in-use measurements. Overheating also contributes to the EPG, as homes which did comply to a building code, may no longer do so, due to the retrofit introduction of air conditioning units (Gupta, 2015). In the UK currently, domestic installation of fixed or portable cooling is low (3%) and increased uptake will increase electrical energy usage (BRE, 2013b).

The ZCH define overheating as *the phenomenon of excessive of prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*. (ZCH, 2015d).

The three main causes of overheating identified are (i) excessive solar gains, (ii) low ventilation rates and (ii) high internal gains. However, air movement, humidity, activity, age, gender, health, clothing are also factors. This makes thermal comfort an individual experience. What one person would find comfortable another may find too hot or too cool. For example, a Passivhaus care home found that whilst staff reported the internal temperatures too high, for residents who were frail and less active, temperatures were more acceptable (Guerra Santin and Tweed, 2013), however this is not always the case (Gupta et al., 2016).

There is a concern that increasing insulation and airtightness levels contribute to overheating risk, but the relationship is not clear. Building modelling is inconclusive, some studies suggest that more energy efficient homes are more at risk (Jones et al., 2016, McGill et al., 2017b), whilst others show that higher levels of insulation and air tightness reduce that risk (CIBSE, 2005), as long as they are combined with appropriate glazing ratios and shading

(McLeod et al., 2013) and access to purge ventilation (Fosas et al., 2018). In-use measurements are also unconvincing, the UK Building Performance Evaluation Program could not draw any conclusions (Palmer et al., 2016) .Occupant behaviour, especially controlling ventilation, seems to be critical in managing risk (NHBC, 2012c, McGill et al., 2017b).

Overheating is not just confined to new homes. In Exeter, 27% of bedrooms in existing homes were overheating (Vellei et al., 2016), this increased to half in London (Pathan et al., 2017), and 88% in Leicester (Lomas and Kane, 2012). 70% of social housing landlords experienced an overheating issue within their existing stock. (ZCH, 2015a).

When specifically looking at Passivhaus homes, small scale studies have shown higher than expected internal temperatures (Sharpe and Morgan, 2014, Ingham, 2014, Sameni et al., 2015), whilst others have not (Schnieders, 2003a). Again ,changing occupant behaviour to manage indoor comfort it critical (Zhao and Carter, 2020) and ensuring that mitigation strategies are applied (Ibrahim et al., 2017, Ridley et al., 2014).

Therefore, overheating affects both new and existing homes, and is not limited solely to energy efficient homes. As summer temperatures increase in the UK with climate change, this overheating risk could be greater (McLeod et al., 2013). As overheating is both an EPG issue (retrofit of air conditioning) and a health issue (increase in excess summer deaths), understanding how ultra-low energy homes such as Passivhaus homes perform in the UK is critical, to increase understanding in how the FHS should look. We look at this in Chapter 3.

1.6 Post Occupancy evaluations

It is recognised that there is a lack of post occupancy evaluation (POE) of buildings in the UK (ZCH, 2014c). The main factors for this are, the lack of a formal framework or indicators, cost of both undertaking POE and the cost of remedying the findings, time constraints, concern about poor performance, unfavourable comparisons, and professional liability issues (Cooper, 2001, Bordass and Leaman, 2005, Durosaiye et al., 2019, Leaman et al., 2010, Hadjri and Crozier, 2009) .

The largest UK domestic POE program was the Building Performance Evaluation (BPE) (2010 -2015). This was the first national post occupancy monitoring of over 100 domestic and non-domestic buildings. Now finished, POE is largely a voluntary activity undertaken by interested stakeholders (Stevenson, 2019).

Where POE does take place, this is typically small scale and forensic, with researchers often unable to draw wider comparisons as a result of the limited sample within the study (Ridley et al., 2013).

There is also a fourth factor that could contribute to the EPG and that is the data gathering process in POE itself.

1.6.1 Uncertainties in monitoring and testing

Collecting reliable data is not without its problems and there are concerns around calibration and effectiveness of sensors, intrusion into domestic homes and the difficulties of different types of metering e.g. pay as you go (Board, 2012). In addition, methodologies such as the co-heating test are still based on assumptions made 30 year ago. This and other tests are in need of further development to reduce the uncertainty of some of the results (ZCH, 2010b, GHA, 2014) . Heat metering is frequently used to collect space heating data, and externally fixed sensors can have a mean error rate of 9% and can be as high as 30%, depending on flow rate and temperature difference (Butler and Abela, 2016). Therefore, as typical data collection methods have some uncertainty, in Chapter 4 we look at other simpler collection methods, which may overcome some of the obstacles to POE.

1.7 Research aim and questions

This thesis aims to evaluate the performance of UK Passivhaus dwellings, specifically looking for evidence of the performance gap in space heating demand and overheating risk. The knowledge gaps identified are outlined in the three research questions below.

Research Question 1. Can a simplified method for temperature and weather normalisation be developed, which can be applied to measured space heating data from dwellings post occupancy, when there is no access to the original building model, or information on the building geometry and specification? Can building models be interchanged and used post hoc to calculate a normalisation factor, to account for varied internal and external temperatures, which can affect the EPG? Are other factors (solar gains, internal gains) relevant when calculating this factor?

Research Question 2. As internal comfort is part of the Passivhaus certification criteria, is there a performance gap between summer internal temperatures and the maximum allowable overheating as defined by the Passivhaus certification method. How does modelling of overheating risk used in PHPP compare with other methods such as CIBSE

TM59 for domestic dwellings? Would the results in one standard (PHPP) predict the results in another standard (TM59) and what are the key lessons to learn?

Research Question 3. How do Passivhaus dwellings in the UK perform once occupied, compared to the space heating prediction from design models (PHPP)? Can sufficient data from enough dwellings be collected to consider the UK application of the energy standard as a whole rather than on a case by case basis. Are there methods which can be applied to maximise data collection, when there is limited data available and how accurate would this data be compared to typical collection methods such as heat metering?

1.8 Thesis outline

Each of these research questions are addressed in the three main chapters (Chapter 2, Chapter 3 and Chapter 4). Each of these chapters are based on a peer reviewed journal paper. The published manuscript is presented in the usual format. Whilst each paper can stand alone with an abstract, literature review, method, results, and discussion, there is a progression of the overall body of the research and the three papers are linked. This is outlined in the preamble and postscript for these three key chapters.

Chapter 1 provides a background to the research area and the gaps identified which led to this thesis. The aims and objectives are outlined, and the three research questions addressed through either, the peer reviewed journals or a paper awaiting publication.

Chapter 2 addresses Research Question 1. Here the difficulty of amending building models predictions, with in- use data for temperature and weather normalisation then there is no access to the original model is addressed. By comparing the outputs from two commonly used building models (SAP and PHPP), using data from low energy homes, the robustness of calculating a normalisation factor is assessed. This is presented in the published paper *Normalising domestic space heating demand using post hoc models.*

Chapter 3 evaluates the risk of overheating in UK Passivhaus homes to address Research Question 2. Using data from 82 dwellings, measured internal temperatures are compared to the Passivhaus standard and CIBSE TM59. By looking at different room and house types, conclusions are drawn the vulnerability of bedrooms and recommendations are made. This is presented in the published paper *Overheating risk in Passivhaus dwellings*

Chapter 4 To address Research Question 3, an analysis of POE data from 97 Passivhaus dwelling from 13 different sites is undertaken to evaluate the overall performance of the standard in the UK. Using the normalisation technique developed in chapter 2, differing internal temperatures for modelling assumptions, are excluded from the EPG and simplified data collection methods are evaluated. This is presented in the published paper *UK Passivhaus and the energy performance gap*.

Chapter 5 Summarises the outputs from the studies in the context of the literature and the aims and objectives of the thesis.

Chapter 2 Normalising domestic space heating demand using *post hoc* models

2.1 Preamble

When buildings use more energy than predicted by design models, a performance gap occurs. As discussed in Chapter 1, there are three main variables which contribute to this; inaccurate building models, poor construction on-site and different-than-predicted user behaviour. To start to gain clarity on this complex issue, it is vital to separate out and quantify any elements which can be identified as contributing to the performance gap. This often means making an adjustment to the original building design model once more accurate final construction data is known, for example, final air pressure tests, refined construction details, boiler makes and models, etc. All of these elements will influence the final space heating demand prediction.

It is also known that internal temperature and external weather affect space heating demand. Therefore, a further refinement could be made to the building model, by inputting this in-use data and recalculating predicted space heating demand. This is the principle of temperature normalisation.

Steady state models used on a domestic scale, such as SAP and PHPP, apply mean monthly external temperatures and fixed target internal temperatures, typically 18°C–20°C. As post-occupancy research shows, homes, often with better insulation levels, are heated to higher internal temperatures (>20°C). This has implications for the interpretation of measured space heating from the field. An adjustment (normalisation) should be made to space heating data, to account for this higher internal temperature, as assumptions could be made about the energy performance gap, which could have been accounted for by this process. However, there is a problem if the original building model is not available, as this adjustment cannot be made using the more accurate field data.

This is addressed by Research Question 1, which asks, *can a simplified method for weather and temperature normalisation be developed, which can be applied to measured space heating data from dwellings post-occupancy, when there is no access to the original building model, or information on the building geometry and specification? Can building models be interchanged and used post hoc to calculate a normalisation factor, and account for varied internal and external temperatures, which can affect the energy performance gap? Are other* *factors (solar gains, internal gains) relevant when calculating this factor? And how accurate would this method be?*

This chapter is based on the journal publication “Normalising domestic space heating demand using *post hoc* models” published in the journal *Building Services Engineering Research and Technology* in 2019. Here the problem of temperature normalisation is addressed, when the original building model is not available. The research is undertaken using the two commonly used domestic building models, SAP and PHPP, and uses measured internal temperature and space heating data from 20 low-energy homes. A temperature and weather normalisation methodology is developed, which supports the research work in Chapter 4. This method, that neither requires the original building model or information about the building itself, allows for normalisation to be applied at a much wider scale, which then generates more accurate reporting of space heating data.

This chapter is based on the journal publication “Normalising domestic space heating demand using *post hoc* models” published in the journal *Building Services Engineering Research and Technology* in 2019.

2.2 Declaration of authorship

<table>
<tr><td colspan="10">This declaration concerns the article entitled:</td></tr>
<tr><td colspan="10">Normalising domestic space heating demand using post hoc models</td></tr>
<tr><td colspan="10">Publication status (tick one)</td></tr>
<tr><td>Draft manuscript</td><td></td><td>Submitted</td><td></td><td>In review</td><td></td><td>Accepted</td><td></td><td>Published</td><td>√</td></tr>
<tr><td>Publication details (reference)</td><td colspan="9">Rachel Mitchell and Sukumar Natarajan
Normalising domestic space heating demand using post hoc models
Building Services Engineering Research and Technology 1 May 2019, Vol. 40(3) 340–359 DOI .10.1177/0143624418816431</td></tr>
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<tr><td>Candidate's contribution to the paper (provide details, and also indicate as a percentage)</td><td colspan="9">The author of this thesis predominantly contributed to formulating the ideas and background work. The method was developed in collaboration with S Natarajan and expanded to include the SAP models. The majority of the experimental work and manuscript writing was undertaken by the author, S Natarajan assisted with visual basic programming in the data analysis and reviewed the paper before publication.
The contribution by each author are as follows
Formulation of ideas: R Mitchell (70%) S. Natarajan (30%)
Background R Mitchell (90%) S Natarajan (10%)
Design of methodology: R Mitchell (65%) S Natarajan (35%)
Experimental work: R Mitchell (80%) S Natarajan (20%)
Analysis: R Mitchell (65%) S Natarajan (35%)
Presentation of data in journal format: R Mitchell (70%) S Natarajan (30%)</td></tr>
<tr><td>Statement from Candidate</td><td colspan="9">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
<tr><td>Signed</td><td colspan="5"></td><td colspan="2">Date</td><td colspan="2"></td></tr>
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2.3 Abstract

Current evidence suggests that the energy performance gap (EPG) between predicted and actual use of energy in buildings is significantly weighted towards under prediction and can be as high as 200%. High-quality modelled and actual data are needed to ensure like for like comparisons (LFLC) when investigating the EPG. Internal temperature (t_i) normalisation, to correct for user preference, is a key process to ensure LFLC but is often hampered by the lack of the original model due to the time lag between design, construction, and occupancy.

Here, we demonstrate the use of models created after data collection – i.e. *post hoc* – as a substitute for original models in evaluating the EPG. The robustness of the internal temperature normalisation factor (f_{ti}) is tested using measured data from 20 Passivhaus homes. The data from each home is inputted into 10 PHPP and 10 SAP models with highly different domestic and non-domestic building configurations, creating 400 model variants. Each variant is further split into four cases of varying internal gains and solar radiation creating a total of 1,600 variants. Results demonstrate that f_{ti} is resilient to differences in building configuration, solar radiation levels and varying internal gains (Standard Error of the Mean<0.02). Even though SEM increases when measured internal temperatures are below base assumptions, the impact of this error on the computed space heating demand is at most 4%. This suggests that *post hoc* models can be a substitute for actual models in evaluating the energy performance gap and that limited site data can still yield robust results.

2.4 Introduction

The energy performance gap in buildings is the difference between the predicted performance from building modelling and the actual measured energy used once the building is occupied (Wingfield et al., 2008, Bell et al., 2010, Gupta and Dantsiou, 2013, de Wilde, 2014). The reasons reported for the performance gap are wide ranging and include aleatory as well as epistemic errors induced via modelling, construction (Trinick et al., 2009, Wingfield et al., 2011, Gupta and Dantsiou, 2013, Grigg and Slater, 2004, ZCH, 2010a, Imam et al., 2017), and user behaviour (Palmer et al., 2016, Gupta and Kapsali, 2015, ZCH, 2014a).

A basic first step is to ensure a like-for-like comparison between the building model and the building as it performs in-use. It would hardly be surprising to find differences between modelled and actual energy performance if, for example, the model assumed different indoor temperatures than those observed. Indeed, it is well-known that the difference between indoor and outdoor temperatures (ΔT) strongly influences space heating demand (Palmer et al., 2011, Layberry, 2009, Simoes N et al., 2016, Majcen et al., 2013) and each 1ºC increase in internal temperature translates to a 10% increase in space heating in typical models. In many steady-state models, which are the most commonly used for domestic scale buildings, ΔT is used as the basis for calculating heating and cooling degree days[1] (CISBE, 2006), which are then used in the modelling to estimate heat losses and heating demand (Mourshed, 2012).

Steady-state building simulation models such as Passive House Planning Package (PHPP) and the UK's Standard Assessment Procedure (SAP)[2] assume monthly fixed internal temperatures and regional climate data to generate degree days (Mead and Brylewski, 2010, Feist et al., 2015b). In reality, annual weather patterns will be different and site-specific weather may vary from that collected at a regional weather station, which may be some distance from the site. These differences in external temperatures (T_e) could result in higher or lower heating demand than predicted during modelling (CIBSE, 2006). In addition, occupants may heat their homes to higher than assumed internal temperatures (T_i) or for longer, for comfort reasons (Exner and Mahlknecht, 2012, Vadodaria, 2014), which will result in different degree day calculations. Other factors such as elevation, solar radiation, micro climates and the heat island effect can also result in inaccuracy of average weather data for a specific site, and therefore under or over estimates of heating demand (Layberry, 2009, Kershaw et al., 2010). Since each of these is essentially an input to the model, any differences arising between model outputs and observed data should be isolated from differences in model inputs. This is the standard process of normalization.

George Box's well-known aphorism that 'All models are wrong, but some are useful' (Box, 1979) suggests that when examining the performance gap, the goal must be to assess whether a given model is a 'good enough' representation of a building's performance *provided the model inputs are a 'good enough' representation of reality*. This is obviously complicated when the original model used to construct the building is itself unavailable. Hence, the goal of this paper is to ask whether a model created after a building is constructed – i.e. *post hoc* – is suitable for use in energy studies. In particular, we wish to examine how sensitive the temperature normalisation procedure is to differences in other model inputs, which could be a major source of uncertainty in the creation of *post hoc* models.

[1] Using either a 'base' temperature or the internal temperature.

[2] It is noteworthy that although SAP was developed as a compliance tool and not a tool for predicting energy use, it is widely used as such due to its ease of use and inheritance from the more robust BREDEM class of models.

2.4.1 Temperature Normalisation Methods and Degree Days

Temperature normalisation allows for an adjustment for differences in measured internal and external temperatures compared to model assumptions. Without normalisation, inferences could be made about the gap between modelled estimates and measured space heating demand (energy performance gap), which could be accounted for by the differences between modelled, and actual, internal, and external temperatures. There are several approaches to temperature normalisation, as discussed below.

CIBSE TM41 describes a simple method where weather related heating loads are divided by local annual degree days and multiplied by the UK 20-year average degree days (usually 2462K Day based on a 15.5°C base internal and external temperature) to allow the comparison of buildings from different regions (CISBE, 2006).

$$Q_{H(normalised)} = Q_{H(measured)}\ x\ UK20\ average\ annual\ degree\ day\ value \qquad \text{(Equation 1)}$$

Where:

$Q_{H\ (measured)}$ = measured space heating demand

A variation on this approach calculates the ratio between actual heating degree days and average heating degree days, this ratio is then applied to space heating demand to normalise (Mahapatra and Olsson, 2015).

$$Q_{H(normalised)} \left(\frac{Average\ annual\ degree\ days}{local\ annual\ degree\ days}\right)\ x\ measured\ space\ heating\ demand \qquad \text{(Equation 2)}$$

However, these approaches are based on fixed internal temperature assumptions, which in the UK is usually a base temperature of 15.5°C plus an assumption for internal gains, giving a total of 18.3°C, and only considers variations in external temperatures. More accurate normalisation methods should take into account site specific base temperatures, as using the standard technique described above, will produce incorrect results for buildings with lower or higher base temperatures (CISBE, 2006). Other factors such as solar radiation and internal gains will also affect space heating demand, and these are not included in the CIBSE method.

Berggren and Wall (Berggren and Wall, 2017) describe two methods for energy normalisation:

1) A static method includes correcting for variations in internal temperatures using the assumption of a percentage increase or decrease in space heating demand based on deviation of internal temperatures from the modelling assumptions. Here heating is

adjusted by 5% for each degree difference between modelled and measured internal temperatures.

$$Correction\ factor\ (cf) = (1 + (T_{modelled} - T_{measured}) * 0.05) \qquad \text{(Equation 3)}$$

Where:

$T_{modelled}$ = target internal temperature assumed in the building model

$T_{measured}$ = measure internal temperature

2) A dynamic method calculates the ratio of energy demand from the building model under normal conditions, with an updated model with actual building use and external temperatures.

Both these approaches consider internal temperatures and are therefore an improvement on TM 41.

The EU-funded CEPHEUS research project (Schnieders, 2003a), developed a normalisation methodology to adjust for fluctuating internal temperatures, taking into account measured external temperature and solar radiation. This method of normalisation allows for location and time specific weather data (external temperature and solar radiation) to be used and for monthly variations in internal temperatures to be accounted for, using the project specific PHPP assessment sheets. It is a variation of the one proposed by CIBSE in TM 41 where the ratio of average heating degree days and actual heating degree days is calculated and is an improvement as solar radiation is also taken into account, and is similar to the dynamic method described by Berggren, but using steady state simulation software (CISBE, 2006, Berggren and Wall, 2017). Hence, we take the CEPHEUS method as the current state of the art for normalisation in steady state simulation.

The method of calculation is given in below.

Step	**Variable to compute**	**Explanation**
Step 1	$Q\ Heating_{measured}$	Measured annual space heating demand [kWh] the real dwelling.

Step 2	$Q\ Heating_{20}$	Annual space heating demand [kWh] summed from monthly values in PHPP using measured monthly external temperatures and solar radiation manually inputted into the 'climate' sheet. Use the standard internal temperature of 20˚C in the 'verification' sheet. Sum monthly heating demand to calculate $Q\ Heating_{20}$.
Step 3	$Q\ Heating\ _{real}$	Same as $Q\ Heating_{20}$ but with measured monthly internal temperatures, manually inputted into the 'verification' sheet.
Step 4	Calculate normalisation factor (f_{ti})	$f_{ti} = \frac{Q\ Heating_{20}}{Q\ Heating_{real}}$
Step 5	Apply normalisation factor to measured space heating	$Q\ Heating_{norm} = QHeating_{measured} * f_{ti}$

Table 5. Summary of normalisation method from CEPHEUS (2003). The 'climate' and 'verification' sheets refer to those sheets in PHPP that contain the external weather data and input / output data, respectively. These are standard names though minor variations exist between versions.

2.5 Building modelling tools

In this paper, we consider two steady-state building energy modelling tools widely used in the UK:

2.5.1 Passive House Planning Package (PHPP):

PHPP is a building energy calculation tool developed by the Passive House Institute in Germany. It is used to design to and demonstrate compliance with, the Passivhaus Standard and was first published in 1998. Since then, there have been several revisions and the current version (V9) allows the tool to show compliance with near zero energy buildings

(NZEBs) in line with the EU Energy Performance in Buildings Directive (EPBD). PHPP uses the principles of BS EN ISO 13790 with additional algorithms to calculate both space heating demand and heating loads (Feist et al., 2015b, Hopfe and McLeod, 2015).

2.5.2 Standard Assessment Procedure (SAP):

SAP is the UK Government's methodology for measuring the energy performance of dwellings and for calculating Energy Performance Certificates (EPCs). SAP is based on the Building Research Establishment (BRE) Domestic Energy Model (BREDEM) and is compliant with BS EN ISO 13790 (BRE, 2013c). The main outputs of SAP (2012) are the SAP rating, Dwelling Emission Rate (DER) and Fabric Energy Efficiency (FEE), which are used to show compliance with Approved Document Part L1A of Building Regulations. All new domestic dwellings in the UK will be subject to a SAP assessment. The current version is SAP (2012).

The shared philosophy and general compliance with BS EN ISO 13790 allows us to compare results from both tools. However, differences in implementation necessitate a careful consideration of the parameters involved in the temperature normalisation process. These are discussed further below, specifically with respect to PHPP (v9) and SAP (2012).

2.5.3 Space heating demand calculations

PHPP (v9) and SAP (2012) calculate monthly space heating demand following EN 13790:2008. This calculation is based on fixed and constant monthly internal and external boundary conditions (Hopfe and Hensen, 2011). Within PHPP (v9) it is possible to change average monthly external temperatures and solar radiation in the 'climate' sheet and internal set temperature in the 'verification' sheet. In SAP (2012) these conditions can be changed within an excel spreadsheet version of the SAP (2012) worksheet.

The formula to calculate the space heating demand (Q_H) is the energy balance between heat losses through the building fabric (transmission losses Q_T) and ventilation losses (Q_V) and heat gains (solar (Q_S) and internal or incidental gains (Q_I)) and is shown in equation 4.

$$Q_H = \left((Q_T + Q_V) - (Q_S + Q_I)\right) \quad \textit{(Equation 4)}$$

In addition, both PHPP and SAP (2012) calculate a utilisation factor (η_H) which relates to how much internal gains can be usefully employed in a dwelling (Feist et al., 2015b, BRE, 2013c). Using this equation, PHPP will calculate the gains and losses and if this difference is greater than 0.1kWh then the period under consideration will be included in the calculation of Q_H. (Schöner et al., 2013). SAP (2012) excludes any heating demand in the summer months (June, July, August) in the space heating demand calculation (BRE, 2013c).

Even in a well-insulated dwelling such as a Passivhaus, the heat losses through the opaque elements will be the largest element of the heat loss calculation (Schöner et al., 2013). PHPP calculates transmission heat losses from the measured area (m²), U value (Wm^2K^{-1}), reduction factor and heating degree hours measured in kilo-Kelvin hours per year ($kKha^{-1}$). Heating degree hours are shown as G_t. Essentially, a heating degree hour (G_t) is the length of time (h) a degree of heating (K) is required. The number of hours will depend on the external temperature and internal temperature (Hopfe and McLeod, 2015). G_t is calculated from the following

$$G_t = \left((T_i - T_e)\, x \frac{t}{1000}\right) \qquad \textit{(Equation 5)}$$

Where,

t is the length of time under review in hours (h)

T_i is internal temperature (generally fixed at 20ºC)

T_e is average monthly external temperature (ºC)

Figure 1 gives a sample calculation from PHPP (v9) showing the calculation of transmission losses using these values.

(This page displays the sums of the monthly method over the heating period)

Climate:	South East England	Interior temperature:	20 °C
Building:	Wishanger EcoHouse	Building type/use:	detached
Location:	Headley	Treated floor area A_{TFA}:	545.9 m²
Spec. capacity:	204 Wh/(m²K) (Enter in "Summer" worksheet.)		

	Building element	Temperature zone	Area m²		U-value W/(m²K)		Month. red. fac.		G_t kKh/a		kWh/a	per m² Treated Floor Area
1.	Exterior Wall - Ambient	A	417.9	*	0.182	*	1.00	*	71	=	5368	
2.	Exterior Wall - Ground	B		*		*	1.00	*		=		
3.	Roof/Ceiling - Ambient	A	625.5	*	0.104	*	1.00	*	71	=	4569	
4.	Foor slab/ basement ceiling	B	633.0	*	0.102	*	1.00	*	45	=	2879	
5.		A		*		*	1.00	*		=		
6.		A		*		*	1.00	*		=		
7.		X		*		*	0.75	*		=		
8.	Windows	A	109.6	*	0.838	*	1.00	*	71	=	6477	
9.	Exterior Door	A	8.4	*	0.789	*	1.00	*	71	=	468	
10.	Exterior TB (length/m)	A	493.0	*	0.035	*	1.00	*	71	=	1232	
11.	Perimeter TB (length/m)	P	122.0	*	0.040	*	1.00	*	45	=	218	
12.	Ground TB (length/m)	B		*		*	1.00	*		=		
	Transmission Heat Losses Q_T									Total	21211	38.9 kWh/(m²a)

Figure 1. Sample transmission loss calculation for a single domestic dwelling (monthly method sheet PHPPv9).

SAP (2012) uses a similar calculation methodology to PHPP. Space heating demand is the balance between heat losses through the building fabric and ventilation and solar and incidental gains. SAP (2012) calculates the heat loss rate (L_m) in Watts for both building fabric and ventilation using **Error! Reference source not found.**equation 6.

$L_m = h_c(T_i - T_e)$ (Equation 6)

Where,

h_c is the heat transfer coefficient taken as sum of fabric and ventilation losses ($W/m^{-1}K$)

T_i is mean internal temperature (see below) (ºC)

T_e is average monthly external temperature (ºC)

2.5.4 Internal temperatures and climate data

For a domestic dwelling unless there is a justified case, in PHPP (v9) the internal temperature will be set at 20ºC. In SAP (2012), internal temperatures within the model are based on two zones and there are separate calculations for the living area and the rest of the dwelling. It is assumed that the living area is heated to 21ºC and the rest of the dwelling to a lower temperature based on heating controls and the heat loss parameter (HLP) calculation. Therefore, less energy efficient homes (with higher HLP) will be modelled on lower internal temperature assumptions and more highly efficient homes will be modelled on internal temperature assumptions more in line with PHPP (v9). The calculation method for mean internal temperatures can be found in Table 9 in the SAP (2012) guidance (BRE, 2013c).

A target whole dwelling internal temperature of 20ºC is in line with mean measured internal temperatures in new and existing dwellings within the UK (Palmer et al., 2011, Gill et al., 2010, Vadodaria, 2014). However, actual temperatures from which this mean is derived range from 16ºC to 23ºC (Vadodaria, 2014, Palmer et al., 2011). Post occupancy evaluation (POE) of Passivhaus dwellings shows an average winter indoor temperature of 21.1ºC ranging between 20ºC and 24ºC (Feist et al., 2005, Exner and Mahlknecht, 2012). This difference between a population mean and the actual sample reflects the variation in indoor temperatures and should be considered when undertaking temperature normalization.

In PHPP (v9) monthly average external temperatures are taken from the ‘Climate’ sheet. Climate data can be obtained from embedded PHPP files, from software such as Meteonorm or from user inputted data. Within PHPP there are currently 22 embedded climate zones for the UK which correspond to the BRE weather regions used within SAP (2012). Regional weather files are only used in SAP (2012) for some calculations, and for space heating loads rather than using regional weather, SAP (2012) currently uses a UK average weather file based on regional data from the East Pennines.

2.5.5 Heat gains

Heat gains are calculated from solar and internal sources and in well insulated homes, internal and solar gains can contribute a significant proportion of the heat balance within a dwelling (Henderson, 2009).

Solar gains in PHPP (v9) and SAP (2012) (Q_S) is calculated using the elements in equation 7.

$$Q_S = r \cdot g \cdot A_W \cdot G \qquad \textit{(Equation 7)}$$

Where,
r is the reduction factor which includes the frame to window ratio, shading, dirt, and angle of inclination
g is the solar energy transmission coefficient for the glazing or g-value for the window
A_W is the rough window opening area (m^2) and
G is the total solar radiation in the heating period ($kWhm^2a^{-1)}$)

Changes in solar radiation will vary the incidence of gains through both opaque and transparent building elements. The relationship between high solar radiation and space heating demand is not clear, especially in homes with triple glazing where solar energy transmittance g-values will be lower compared to single and double glazing (Manz and Menti, 2012). Some research shows that high levels of solar radiation do not always translate into high levels of solar gain and external temperature is a more dominant factor in the estimation of heating (and cooling demand) (McGilligan et al., 2011), or that high radiation can mean higher space heating, as clear skies lead to cooler nights (Danov et al., 2013). Other studies show that solar gains through triple glazing can be significant in winter if glazing areas are large (Manz and Menti, 2012).

Internal heat gains (IHG) account for heat generated from cooking, dishwashing, laundry, lights, consumer electronics, hot water distribution and metabolic gains from occupants (Grant, 2014). For a Passivhaus dwelling, internal gains were generally fixed at 2.1 Wm^{-2}. The method for calculating internal gains has been amended in the new update of PHPP (v9) to better reflect the gains in smaller house sizes and higher electrical loads (Grant, 2014). Internal gains are now on a sliding scale from a maximum of 4.1Wm^{-2} for very small dwellings (≤25^2 TFA) to a minimum of 2.1 Wm^{-2} for dwellings with TFA $\geq$ 300m^2 (PHI, 2015a). An example of the change in IHG calculation in PHPP (v9) is given in Table 6.

TFA (m^2)	Original IHG in PHPP v8 (Wm^{-2})	IHG calculated in PHPP v9 (Wm^{-2})
40	2.1	3.4
65	2.1	2.9
90	2.1	2.7
120	2.1	2.5

Table 6. Change in internal heat gains (IHG) based on TFA using PHPP (v9).

Increasing internal gains for smaller buildings will reduce space heating demand, as more heat gains are attributed to IHG in the energy balance. For the UK, where homes tend to be smaller this change will facilitate meeting the Passivhaus standard.

Revisions in SAP (2012) have also addressed internal gains calculations. Earlier versions of SAP (2012) assumed much higher internal gains and occupancy rates compared to PHPP (v9). For less energy efficient homes these differences had a smaller influence, but in energy efficient homes such as Passivhaus or other low energy designs, internal gains assumptions could account for more than half the heat gains, this difference will impact on the space heating demand calculation (AECB, 2008). Rather than using a fixed amount based on floor area, separate calculations, often based on assumed occupancy levels (which are linked to floor area), are made for metabolic, lighting, appliances, cooking, pumps and fans and water heating gains set against evaporation losses. Even so, in SAP (2012) the revised internal gains assumptions are still higher than PHPP (v9).

The influence of occupancy levels, internal temperatures and appliance use in both Passivhaus and highly insulated homes has been demonstrated using dynamic modelling and it was found that internal temperature, airflow behaviour and appliance use were significant factors and occupancy levels less so (Blight and Coley, 2013, Ruellan et al., 2016).

2.5.6 Other differences

SAP (2012) and PHPP(v9) both calculate space heating requirement based on EN 13790. Steady state fabric and ventilation heat losses are calculated, with solar and internal gains subtracted, and degree days applied, but there are differences between the two models which are summarized in Table 7. These differences were more marked in previous versions but have been reduced with the revisions in SAP (2012) and PHPP (v9) (Reason L, 2008, Weeks, 2014, Koch, 2015, Tuohy and Davis Langdon, 2009).

	SAP (2102)	PHPP (v9)
Dimensions	Internal measurements	External measurements
Internal floor area for energy and carbon calculations	Gross internal area	Treated floor area typically 10% less than gross internal floor area
Solar gains	Based on standard window sizes, shading measured in less detail	More detailed – each window is separately modelled for solar gain and shading
Internal gains	Standard assumptions and can be 100% higher than PHPP	Assumes best practice in choice of lighting and appliances
Ventilation and infiltration	Based on air permeability rates	Based on air change rates
Internal temperature	Living room fixed at 21°C, rest of the dwelling varies with efficiency of building fabric.	Fixed at 20°C
External temperature	Average UK data	Location and altitude specific

Table 7. Differences between SAP (2012) and PHPP (v9). Space heating calculation.

The impact of these differences has been researched and despite the models producing different outputs for heat losses and gains, when space heating demand alone was calculated these differences were less marked: SAP (2012) overestimated space heating by 2.8 kWh/m^2 compared to PHPP (v9) assessments for the same buildings (Koch, 2015). Therefore, whilst there are differences between PHPP and SAP, there are sufficient similarities in the way that space heating demand is modelled. Hence, both building models can be used to test the calculation of a normalisation factor and allow for comparison.

2.6 Method

Since the CEPHEUS method represents the current state of the art for temperature normalisation, we use it as the starting point for our investigation. Our primary hypothesis is that building form and size have no significant impact on the accuracy of the calculation of the normalisation factor (f_{ti}) and therefore access to the site specific PHPP or SAP assessment is not critical. If true, this would simplify the normalisation process and be useful in improving post occupancy evaluations, as this adjustment could be made when the site specific PHPP or SAP sheet may not be available for commercial or other reasons.

In addition, we test the impact of varying internal and solar gains on the normalisation, given that these could have a significant effect on space heating demand, in highly insulated dwellings such as Passivhaus.

The chosen methodology for testing our main hypothesis was:

A. Collect post occupancy data on internal and external temperatures, solar radiation, and space heating demand from 20 certified Passivhaus dwellings. Twenty dwellings were deemed sufficient for this analysis provided they were reasonably inhomogeneous (i.e. not of only one or two types / sizes).
B. Create *10 post hoc* models in PHPP covering a wide range of building typologies, treated floor areas and designs.
C. Input data from each building in Step A into every building model in Step B, varying internal and external temperatures following the CEPHEUS method (see Table 1).
D. Split each model in Step C into four Cases (See Table 5):
   - Case 1. Solar gains per model default, internal gains fixed.
   - Case 2. Solar gains per model default, internal gains varied using PHPP (v9).
   - Case 3. Locally collected solar gains, internal gains fixed.
   - Case 4. Locally collected solar gains, internal gains varied using PHPP (v9).
E. Compute the temperature normalisation factor (f_{ti}) for each *post hoc* model variant created in Step D (n_{PHPP} = 20 x 10 x 4 = 800).
F. Compare the standard deviation (SD) and the standard error of the mean (SEM) for the computed f_{ti}s in Step D. The SD assesses the spread of the computed f_{ti}s and the SEM indicates how well the computed means estimate the population mean. The smaller the SD, the more robust the f_{ti} and the smaller the SEM the greater the confidence that mean f_{ti} is representative of the population (Walker, 2010). In instance the population would mean additional calculations of f_{ti} .
G. Repeat steps B to E using a standard SAP (2012) worksheet, creating n_{SAP} = 800.

For Step A, we obtained data from 20 Passivhaus homes located in the UK (for dwelling types see Appendix 2). The quality thresholds for inclusion in this set were:

- All dwellings to be certified Passivhaus
- Data be available on space heating and internal temperature
- If site specific weather data is unavailable, a suitable local weather station must exist.
- Data available for at least 12 months.

For Step B, 10 PHPP models were created using data from 5 domestic and 5 non-domestic buildings, whose data is summarized in Table 8. All the PHPP building models met the Passivhaus standard in terms of U-values, air tightness etc but each building model had a different specification. This provided sufficient means for testing a variety of realistic sizes and shapes, since these data are sourced from real buildings.

Domestic Building Type	TFA	PHPP version	Non-Domestic Building Type	TFA	PHPP version
Single dwelling A	$120m^2$	8.5	Community Centre A	$430m^2$	8.5
Single dwelling B	$300m^2$	1	Community Centre B	$665m^2$	1
Single dwelling C	$600m^2$	1	Education building	$300m^2$	7.2
Block of 22 apartments	$1420m^2$	8.4	University building	$2800m^2$	9.3
Row of 4 town houses	$350m^2$	7.1	Office	$550m^2$	1

Table 8. Summary of domestic and non-domestic building types PHPP.

All the PHPP assessments were undertaken in earlier versions of PHPP (v9), as these were readily available. All the 20 dwellings from which post occupancy data had been collected had a TFA of less $300m^2$. However, under the new assessment method for internal heat gains in PHPP (v9) these dwellings would have been assigned higher internal gains than the constant of $2.1Wm^{-2}$ used in earlier versions of PHPP. Hence, Cases 2 and 4 test the effect of using the PHPP (v9) values. This is summarized, together with the impact of default and localised solar gains and the corresponding SAP options, in Table 9. Note that internal gains default is different in SAP (variable) and PHPP (fixed, prior to v9).

		Internal gains data	
		Fixed (2.1 Wm^2)	**Variable (PHPP v9 *or* SAP (2012))**
Solar radiation data source	PHPP "Climate sheet regional data" *or* SAP (2012) climate data table U3	Case 1	Case 2
	Real data from CEDA	Case 3	Case 4

Table 9. Summary of four Cases: Case 1 uses the PHPP/SAP (2012) default setting for solar gain and fixed internal gains. Case 2 replaces fixed internal gains with varied internal gains based on floor area. Case 3 replaces PHPP/SAP solar radiation data with geo-temporally correct observed solar radiation data from the Centre for Environmental Data Analysis (CEDA) (Met Office, 2006) and uses fixed internal gains. Case 4 uses internal heat gain settings depending on treated floor area and solar radiation data from CEDA (as Case 2).

The following method was applied for each of the four Cases in PHPP:

1) The PHPP climate sheet was changed to reflect the location and altitude for the specific site where post occupancy data was collected.
2) To calculate $Q\ Heating_{20}$The average monthly external temperature for each year of the monitoring was inputted in the PHPP 'climate' sheet. The internal temperature was set at the standard PHPP certification level of 20ºC. The space heating demand for each month from the 'Heating' Sheet was extracted and summed for the year. This gives the annual space heating demand for $Q\ Heating_{20}$.
3) To calculate $Q\ Heating_{real}$. The average monthly external temperature from monitored data was inputted in the PHPP 'climate' sheet. For the same months, the average monthly measured internal temperature was inputted into the PHPP 'verification' sheet.' The subsequent monthly heating demand was taken from the 'heating' sheet and summed to give the annual space heating demand. This gives the annual space heating demand $Q\ Heating_{real}$.

The normalisation factor was then calculated as

$$f_{ti} = \frac{QHeating_{20}}{QHeating_{real}} \qquad \text{(Equation 8)}$$

The method described above was then replicated using SAP (2012) worksheets. Internal and external temperature data from the 20 dwellings was inputted into 10 different SAP (2012) worksheets. To allow comparison with Q Heating $_{20}$, the internal temperature of the living room was set to 20°C (as opposed to 21°C default in SAP (2012)). To test the robustness of the method, the SAP (2012) assessments from different dwelling types with varying floor areas were selected. The building fabric of these dwellings included Passivhaus and low energy homes, in addition some less efficient dwellings were included to test the robustness of the method. As SAP is for domestic dwellings, there were no non-domestic examples in the sample. Table 10 gives a summary of the dwelling types.

Domestic Building Type	Gross internal floor area	Domestic Building Type	Gross internal floor area
5 bed detached house	228 m^2	2 bed house	79 m^2
4 bed detached house	123 m^2	1 bed flat	42 m^2
4 bed detached house	300 m^2	2 bed flat	72 m^2
3 bed detached house	205 m^2	3 bed flat	95 m^2
3 bed town house	110 m^2	1 bed flat conversion	49 m^2

Table 10. Summary of domestic building types for SAP (2012).

2.7 Results

2.7.1 Calculation of normalisation factors in PHPP (v9) and SAP (2012)

Figure 2 is a box and whisker plot of the raw normalisation factors calculated from the measured internal and external temperature data from the 20 dwellings, for each of the 4 Cases in PHPP and SAP (2012). The results show that for 16 out of the 20 dwellings, there is a narrow range of variation between the normalisation factors calculated. However, for dwellings 1, 4, 16 and 17, the range of f_{ti} is much wider with the greatest range in Case 2 and 4 PHPP. SAP (2012) calculated a narrower range of normalisation factors across these four cases compared to PHPP. For all other dwellings, there was very little difference between the normalisation factors calculated in PHPP and those made in SAP (2012). To simplify further reading, we collectively term dwellings 1, 4, 16 and 17 as Dwelling Outliers (DO).

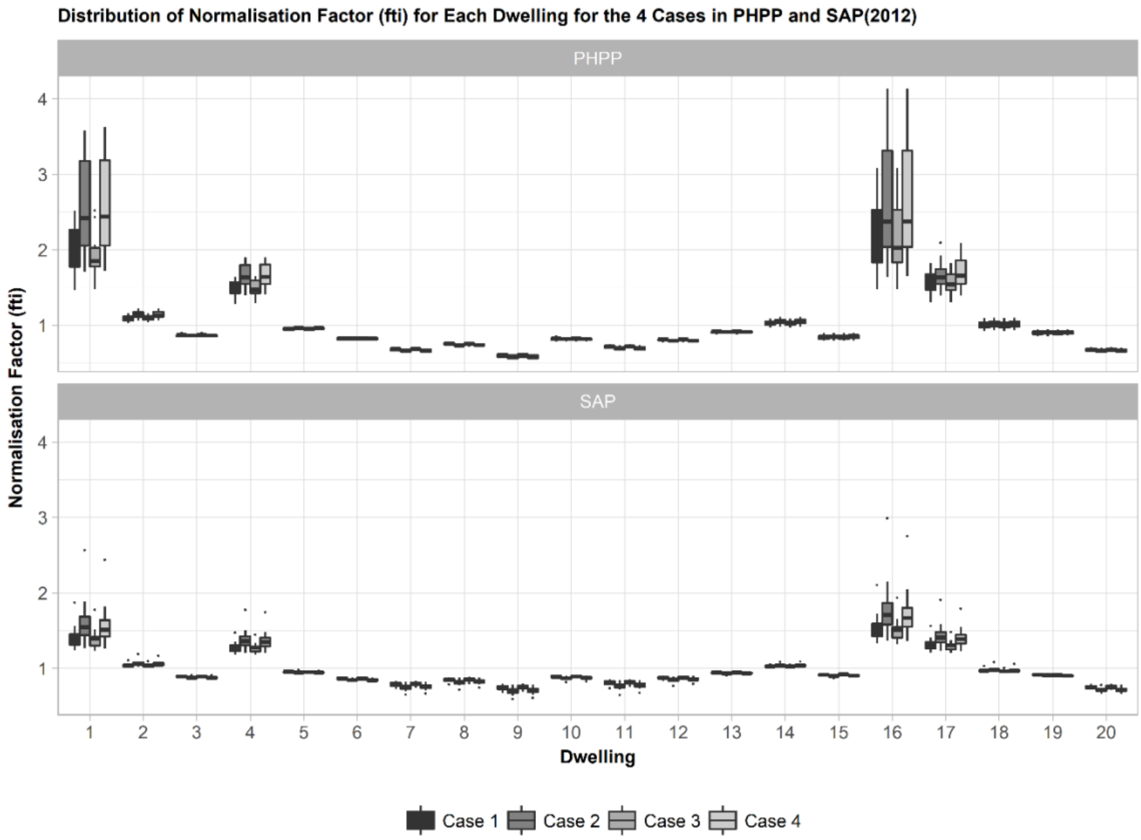

Figure 2 Distribution of the 10 calculated normalisation factors for each dwelling for each Case (PHPP) and SAP (2012) (see Table 6 for the definition of each Case). In each plot, the bar shows the mean, and the box the inter-quartile range.

Variation is further demonstrated by the standard deviation (SD) and the standard error of the mean (SEM) of the normalisation factors. Figure 3 shows all 4 Cases tested in PHPP and SAP (2012). We find that SD (f_{ti}) < 0.06 for non-DO dwellings and >0.07 SD (f_{ti}) < 0.82 for DO dwellings. The widest range of variation is found within Cases 2 and 4 where varied internal gains were modelled. This variation in SD is greater in PHPP than SAP (2012).

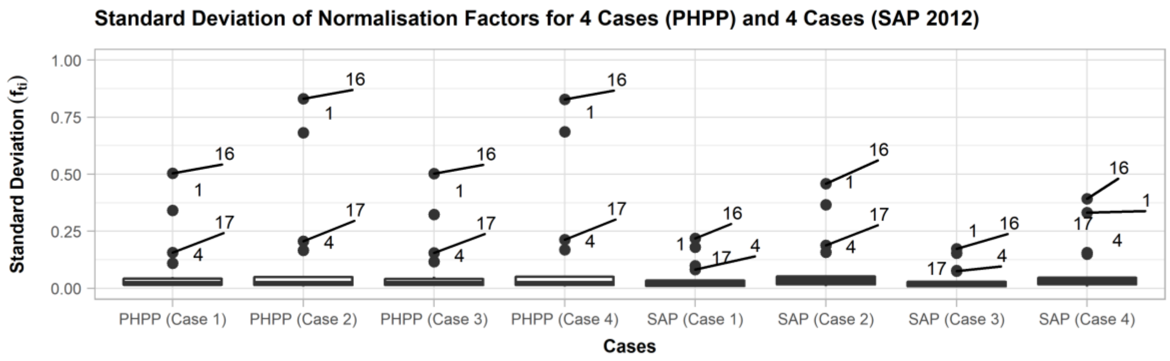

Figure 3 Box and whisker plot of the SD of the 10 normalisation factors (f_{ti}) for the 4 Cases (PHPP) and SAP (2012) with outliers labelled

The DOs are the same four dwellings as identified in Figure 2 . For all non-DO PHPP and SAP (2012) Cases, the variation in SEM of f_{ti} is very small (SEM<0.02) as shown in Figure 4. For the DOs, in each Case, SEM ranges from 0.03 to 0.26. Again, the largest range of variation between SEM is found within Cases 2 and 4, in both assessments, where varied internal gains were modelled.

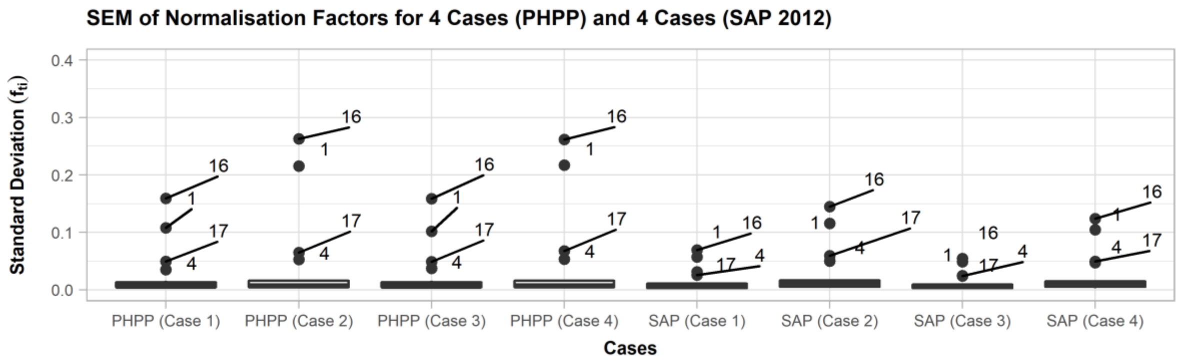

Figure 4 Box and whisker of the SEM of the 10 normalisation factors (f_{ti}) for the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

2.7.2 Impact on space heating demand

The 10 normalisation factors (f_{ti}) calculated for each of the 4 Cases (PHPP) and SAP (2012) were applied to the measured annual space heating demand (normalised by TFA) from the 20 dwellings. Outliers were included in the calculation of f_{ti} for each case.

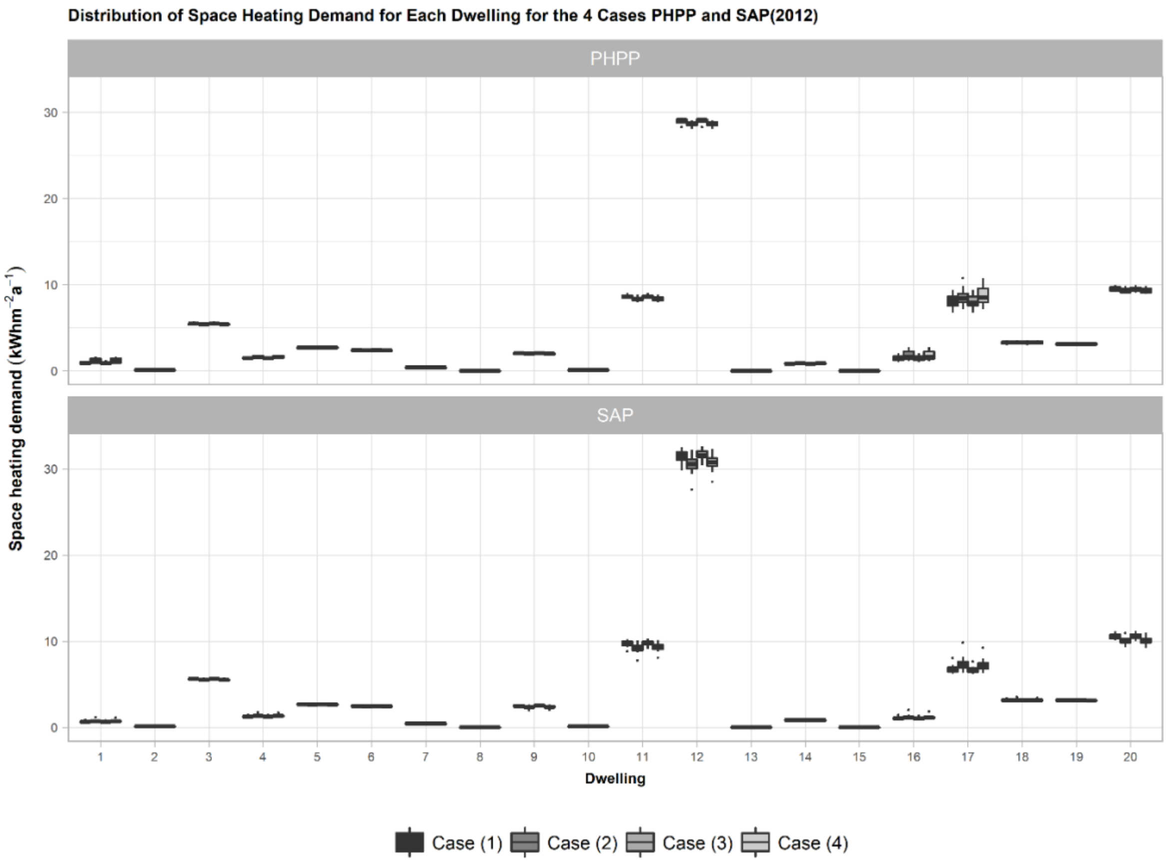

Figure 5. Range of normalised space heating demand (kWha^{-1}) for the 4 Cases in PHPP and SAP (2012).

Figure 5 shows that 10 dwellings had little or no space heating demand (< 1kWhm^{2}a^{-1}). Therefore, for these dwellings, the impact of applying the normalisation factors will be limited. Dwellings 11, 12, 16, 17 and 20, which are primarily characterised by higher space heating demand, showed a wider variation in normalised demand once f_{ti} had been applied. However, even within this group the difference between normalised space heating demand for the 20 dwellings is not large, ranging from 0.5 to 4.9 kWhm^{2}a^{-1}. Differences can also be seen between the PHPP and SAP assessments and these are further analysed below.

The impact of applying the 10 f_{ti}s to space heating demand is demonstrated by the SD of normalised space heating demand for the 4 Cases (PHPP) and SAP (2012) shown in Figure 6 on the following page.

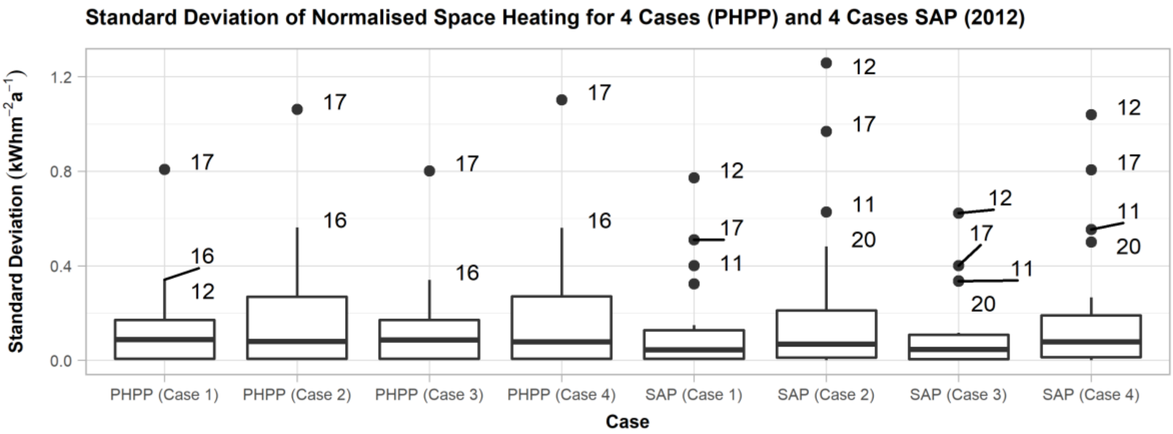

Figure 6. SD of normalised space heating demand for each of the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

The results in Figure 6 show that the distribution of SD of the measured annual space heating demand, when the normalisation factors are applied, for the 4 Cases in PHPP and SAP is very consistent. For Cases 1 and 3, SD is less than 0.9 kWhm^{2}a^{-1}, and for Cases 2 and 4, the SD is less than 1.3 kWhm^{2}a^{-1}. Unsurprisingly, outliers are dwellings with the highest annual space heating demand (see Figure 5). Though DOs are contained in the outliers, non-DO dwellings also appear (e.g. 11, 12, 20), suggesting that space heating demand has a bigger impact on the SDs than f_{ti}. This is supported by the SEM data (Figure 7), which is less than 0.1 for most cases, and the outliers following the same pattern as in Figure 6.

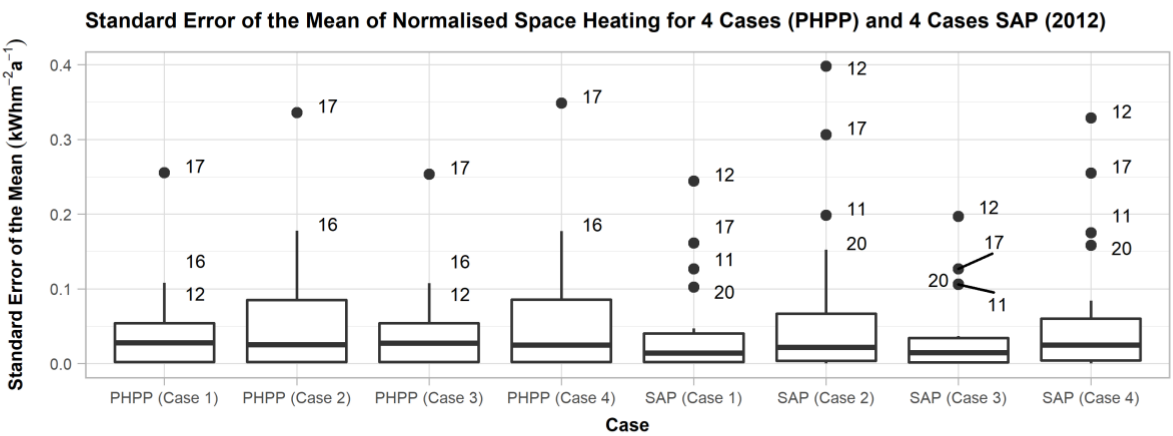

Figure 7. SEM of normalised space heating demand for each of the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

2.7.3 Impact of variables

Here we undertake further analysis of individual variables to understand why the range of f_{ti} is significantly higher in DOs (see Figures 2 and 5) compared to the rest of the dwellings modelled. Since there are only three variables (t_i, IHG, solar) that were manipulated in the modelling, we consider each of these in turn.

2.7.4 Internal temperatures

Within the 20 dwellings, there were variations in average winter internal temperatures. Figure 8 below shows the mean internal temperature during the heating season (October to May) for each dwelling compared to the internal temperature assumed in the PHPP and SAP (2012) assessments (20ºC). 16 of the 20 homes had an internal temperature either the same or above the modelling assumption in PHPP and SAP (2012). DOs had an average internal winter temperature below the assumption in PHPP and SAP (2012) and these homes correspond to the dwellings with the greater range of calculated normalisation factors.

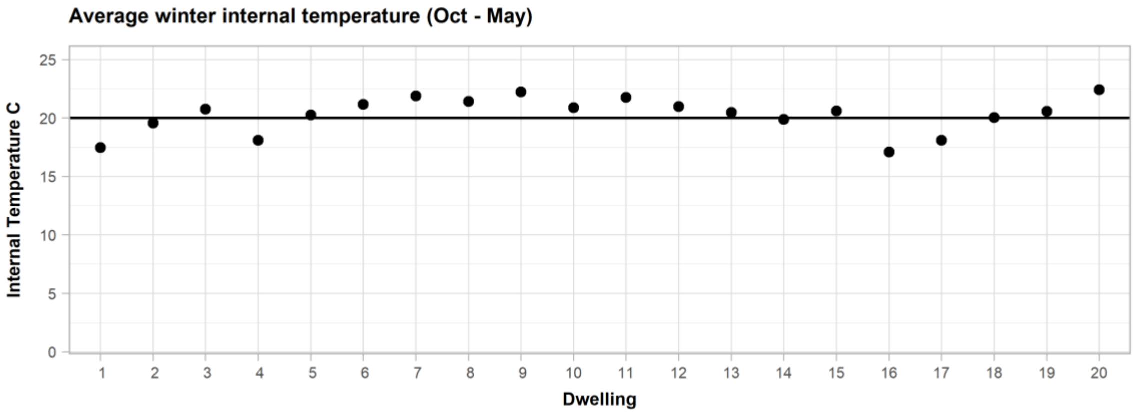

Figure 8. Average measured internal winter temperature (October to May) for each dwelling (circles) compared to the assumed internal temperature of 20ºC (solid line) used in the PHPP and SAP (2012) models.

Average winter internal temperature was plotted against the SD of the f_{ti} for all four cases in PHPP and SAP (2012) (Figure 9, Figure 10).

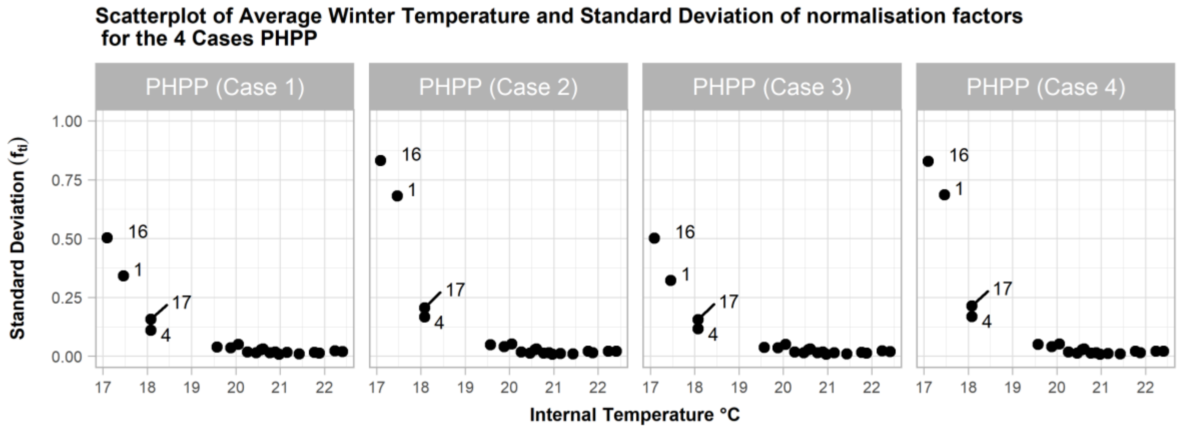

Figure 9. Standard deviation of the 10 normalisation factors (fti) *with measured internal winter temperature for the 4 Cases (PHPP)*

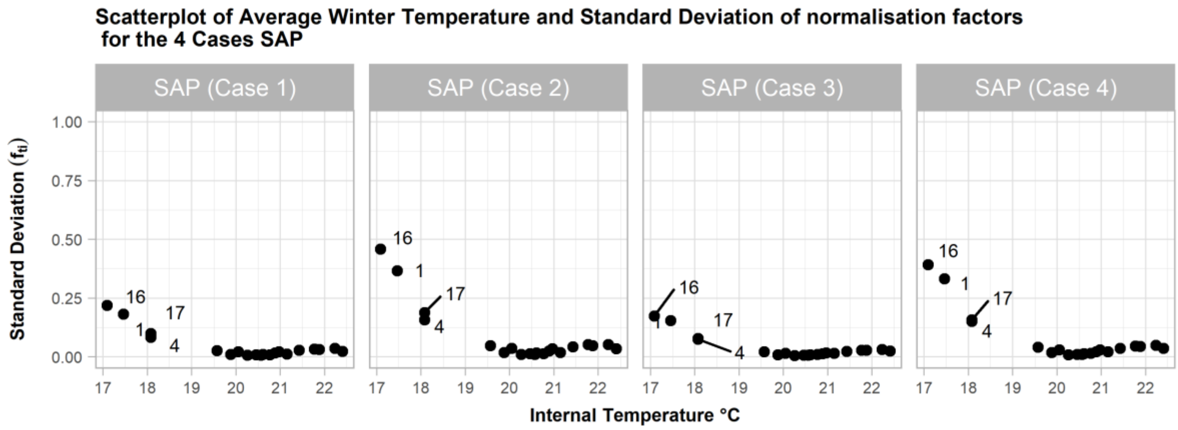

Figure 10. Standard deviation of the 10 normalisation factors (fti) *with measured internal winter temperature for the 4 Cases SAP (2012).*

Figure 9 and Figure 10 suggests that internal temperature has an influence on f_{ti}. Dwellings 1, 4, 16 and 17 had an average winter internal temperature ≤ 18.1ºC and the highest ranges of f_{ti}. This is shown by the increased SD of between 0.1 and 0.81. The lower the measured internal temperature, the higher the range of f_{ti}. Once internal temperatures were close to the modelling assumptions of 20°C, the SD of f_{ti} is below 0.05. When the measured internal temperature rose above the assumption of 20ºC, the range of f_{ti} also remained within this lower range. Therefore, higher internal temperature does not have the same effect on f_{ti} as lower temperatures. This pattern was consistent across all four cases calculated in PHPP and SAP. There is a slightly larger range of normalisation factors in Case 2 and 4, where internal gains were varied, and this is studied next.

2.8 Internal gains

The impact of varied internal gains on the range of normalisation factors (f_{ti}) was considered for Cases 2 and 4 only. The internal gains assumptions were varied to reflect the different TFA according to the methods used in both PHPP (v9) and SAP (2012). Note that there are higher IHG assumptions in the SAP (2012) assessment.

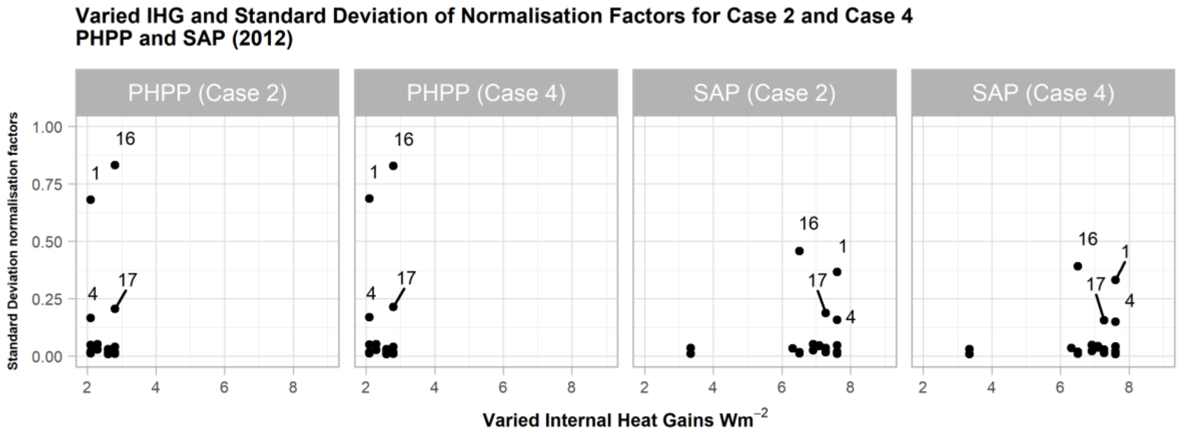

Figure 11. Standard deviation of normalisation factors (f_{ti}) with internal heat gains Cases 2 and 4 only. The number indicates the dwelling ID for each DO.

Figure 11 shows the SD of f_{ti} plotted against the varied internal gains (Wm^{-2}), for Case 2 and Case 4 only. Since DOs have both low and high internal heat gain assumptions in the PHPP (v9) and SAP (2012) assessments, we can conclude that variation in IHG is not influencing the calculation of f_{ti}.

2.8.1 Solar gains

Figure 12 below shows the SD of normalisation factors (f_{ti}) against annual solar radiation, in Cases 3 and 4 where CEDA irradiation readings were substituted for the climate data in PHPP and SAP (2012). The 4 dwellings with the greatest SD are labelled and are all DOs. Since the DOs have both higher and lower measured annual solar radiation, we conclude that solar radiation levels are not influencing the calculation of f_{ti}.

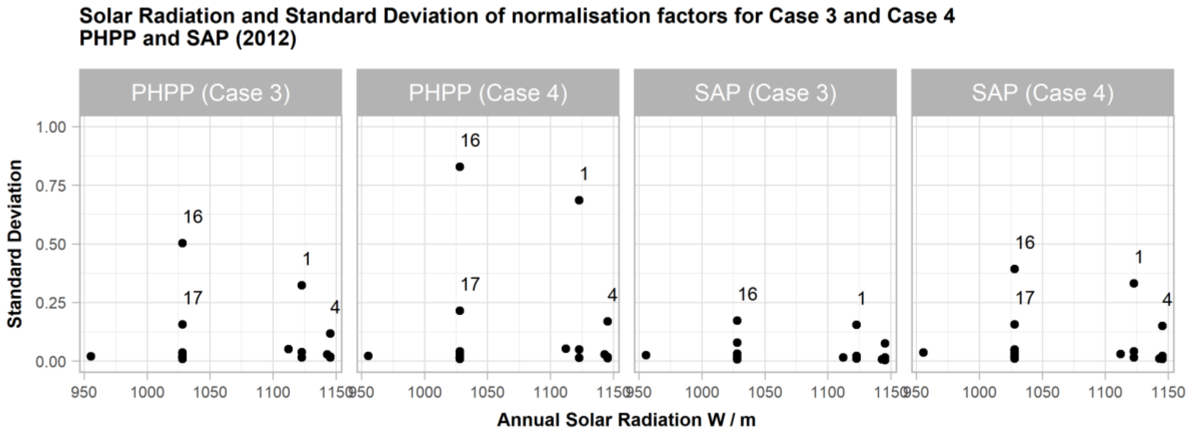

Figure 12. Measured annual solar radiation and SD of correction factors Case 3 and Case 4 PHPP and SAP (2012). The number indicates the dwelling ID for each DO.

2.8.2 Dwelling type

Table 9 lists the dwelling types from which the measured data were taken and demonstrates that there is no relationship between the DO's and a particular type of dwelling.

2.9 Conclusion

Normalising measured space heating energy data enables in-use data to be compared more accurately to building models, by considering the effect of varied internal and external temperatures on space heat demand. Both PHPP and SAP (2012) allow for modifications to be made to the model using locally collected data. Predicted space heating demand can be modified by inputting measured monthly average internal and external temperatures into the PHPP and SAP (2012) assessment sheets. This generates a more accurate heating degree hour calculation for each month which improves annual degree day data, as suggested in CIBSE TM 41. Being able to adjust for these differences between real and modelling temperature assumptions means these factors to be excluded from any performance gap analysis.

When undertaking post occupancy monitoring, the site specific PHPP or SAP assessment may not be available. This means that without an alternative method it would not be possible to undertake normalisation for internal and external temperatures on the measured space heating demand. The results showed that a calculation of a normalisation factor (f_{ti}) can be undertaken without the site specific PHPP or SAP sheets and that a building with a different form and function can be used, as both domestic and non-domestic PHPP assessment sheets were tested. A wide range of buildings types with varying energy efficiency were used in the SAP testing.

For all 4 Cases (PHPP) and SAP (2012), 80% of the calculated normalisation factors had an SD of <0.05 and 80% had a SEM of < 0.02. To investigate why the remaining 20% of dwellings displayed a higher SD and SEM, which were consistent across all four Cases (PHPP) and SAP (2012), we compared them against the three manipulated variables: internal temperature, internal heat gains and local solar radiation data. Analysis demonstrated that there was a clear relationship between variation in the normalisation factors calculated and lower winter internal temperatures. When the average measured internal temperatures were below 20ºC, the temperatures assumed in the PHPP and SAP (2012) calculations, the variation in the normalisation factors calculated increased. This variation was greater in the PHPP assessments compared to SAP (2012) and suggests that the space heating demand calculation may be more sensitive to low internal temperatures, as other factors such as internal and solar gains will make up a greater proportion of overall heat gains. However, normalisation factors were not observed to be influenced by either variable internal heat gains or the use of local solar radiation data. We hence conclude that low internal temperatures exert the greatest influence on the reliability of the normalisation factor calculation.

However, when the normalisation factors are applied to measured space heating demand – which is the variable of interest – the computed variation in t_{fi} has a demonstrably smaller impact. This is shown in additional DOs appearing in the SAP (2012) Cases, when actual space heating demand has a greater influence on variation rather than the calculated normalisation factors themselves. For 90% of the dwellings the SD of normalised space heating demand was less than 1 kWhm^{2}a^{-1} and the greatest SD was 1.27 kWhm^2 a^{-1}. This translates to a maximum standard error of 0.4 kWhm^{2}a^{-1}. Given that the energy consumption for the cases with the greatest standards are typically less than 10 kWhm^{2}a^{-1} (i.e. an overall error of 4%), we conclude that temperature normalisation using a *post hoc* model is appropriate.

The research in this paper has a practical application for dwellings assessed in either PHPP or SAP, as the normalisation factor (f_{ti}) can be calculated using a non-site-specific assessment. The normalisation factor is essentially a correction factor, which takes into account the difference between predicted space heating demand based on modelling assumptions and predicted space heating demand based on actual weather and measured internal temperature data. This difference is calculated as ratio, which can then be applied to measure space heating, to adjust for this variation in model inputs. From the data collected, when measured internal temperatures are close to or above the modelling assumptions then either a PHPP or a SAP (2012) sheet could be used for normalisation as the results were consistent across the two tools. This allows greater flexibility when normalising if only one tool is available and would allow retrospective normalisation using either method.

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2.12 Appendix 1 Definition of terms

Term	Units
Heat transfer co-efficient	$W/m^{-1}K$
Internal heat gains	Wm^{-2}
Solar radiation	W/m
Space heating demand	$kWhm^2a^{-1}$
Temperature	°C

Table 11. Terms and units.

2.13 Appendix 2 Dwelling types with measured data

Table 8: List of dwelling numbers against types. DOs are indicated with a *.

Dwelling Type	Dwelling No.
2 bed end terrace	1*
	4*

	3
	6
2 bed mid terrace	2
	5
3 bed end terrace	7
	9
	10
	11
	13
	14
	16*
	18
3 bed mid terrace	8
	12
	15
	17*
Detached bungalow	19
Detached house	20

Table 12. Dwelling types

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2.15 Postscript

This chapter shows that space heating demand can be normalised using a PHPP or SAP assessment from a different building and that these models can be interchangeable. By testing each model type with the same data, providing internal temperatures do not fall too far below the building model assumptions, an accurate normalisation factor can be calculated, to then be applied to measured space heating demand. By comparing the impact of internal temperatures, solar gains, and internal gains on the calculation of this factor, we conclude that internal temperature is the critical variable. This means that a normalisation calculation can be undertaken with less data. This impacts on time, costs and complexity when collecting data in the field, well-known barriers to undertaking POE (Leaman, 2003, Hadjri and Crozier, 2009).

These results answer the two sections of Research Question 1.

1. Both SAP and PHPP models can be used to calculate the normalisation factor. Indeed, these models can be inter-changed, and the same results calculated. This

means that normalisation can be applied to sites where there is no access to the original building model, or information on the building itself. A different model can be substituted.

2. The results also show that varying solar and internal gains do not influence the calculation of the normalising factor. Internal temperatures are critical. This reduces the amount of data to be collected on-site.

Both these results simplify the process and the quantity of data to be collected on-site, to still yield accurate and meaningful results.

The method developed in this chapter was then applied in Chapter 4. This chapter analyses measured space heating data from Passivhaus dwellings in the UK, which is compared to predictions from the PHPP models. Using measured internal temperature data, where available, normalisation is applied, to ensure this element of the energy performance gap is taken into account, and therefore give a more accurate reporting of the performance of these dwellings.

Chapter 3 Overheating risk in Passivhaus dwellings

3.1 Preamble

Chapter 2 considered one element of the energy performance gap (accurate building models) and how higher-than-predicted internal temperatures in the heating season can explain some differences between the outputs of a building model and measured space heating in-use data. However, Passivhaus is not just a space heating standard, it is also a comfort standard and internal temperatures are a critical part of comfort. Indeed, if internal temperatures, as predicted by PHPP, are over 25°C for >10% of occupied hours, the building will fail to meet the certification criteria at the design stage.

Summer overheating is an increasingly important performance gap issue. If measured internal temperatures are greater than models predict, this not only leads to discomfort; if internal temperatures are persistently high, especially at night, this can be a hazard to health and contribute to excess summer deaths. Therefore, the in-use performance of a Passivhaus building should also include measuring for overheating.

Research Question 2 asks *as internal comfort is part of the Passivhaus certification criteria, is there a performance gap in the UK between internal temperatures and the maximum allowable overheating as defined by the Passivhaus certification criteria? How does modelling of overheating risk used in PHPP compare with other methods such as CIBSE TM59 for domestic dwellings? Do the results compared to one standard (PHPP) also predict the performance compared to the other standard (TM59) and what are the key lessons to learn?*

This chapter is based on the journal publication “Overheating Risk in Passivhaus Dwellings” published in the journal *Building Services Engineering Research and Technology* in April 2019. Here, dry bulb internal temperature data collected from 82 Passivhaus dwellings is analysed. Both methods of measuring overheating risk (PHPP and CIBSE TM59) are applied and evaluated to allow a comparison.

3.2 Declaration of authorship`

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S Natarajan contributed the additional dimension of TM52, the data analysis and review of the paper
The contribution by each author are as follows

Formulation of ideas: R Mitchell (75%) S. Natarajan (25%)
Background R Mitchell (90%) S Natarajan (10%
Design of methodology: R Mitchell (70%) S Natarajan (30%)
Experimental work: R Mitchell (80%) S Natarajan (20%)
Analysis: R Mitchell (65%) S Natarajan (35%)
Presentation of data in journal format: R Mitchell (80%) S Natarajan (20%)</td></tr>
<tr><td>Statement from Candidate</td><td colspan="9">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
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3.3 Abstract

Highly insulated and airtight homes designed to reduce energy consumption, are perceived as having a greater summer overheating risk than less insulated homes. If true, dwellings built to the well-known low-energy Passivhaus standard could be at greatest risk due to the use of superinsulation, especially as the climate warms. Existing studies are inconclusive and even contradictory, mainly due to small sample sizes. Hence, this paper presents the first large-scale overheating risk analysis of UK Passivhaus dwellings using high-resolution internal temperature data from 82 homes across the UK. Both the Passivhaus and the recently published CIBSE TM59 criteria are analysed. Results show that the whole-dwelling Passivhaus standard, which uses a fixed temperature threshold, is met more frequently (83%) than when applied on a room-by-room basis (e.g. only 60% of bedrooms in houses meet the standard). TM59-1A, which uses an adaptive temperature threshold, is easier to meet with 100% of flats and 82% of houses in compliance. However, 55% of bedrooms assessed under TM59-1B fail, with little difference between flats and houses. This is a remarkable finding given that the summers under consideration were either typically mild or cooler than average, and that sleep impairment can significantly affect both physical and mental health. These results suggest that highly insulated dwellings such as Passivhaus, should consider overheating in individual rooms, rather than at whole-dwelling level. Analysis should be undertaken throughout the year with particular attention to bedrooms, using either the good-practice PH-5% exceedance threshold which maps well to TM59-1B, or TM59-1B itself.

Practical Application

Overheating risk in new dwellings is an industry concern. Having the correct tools to predict this risk at design stage is important to help design comfortable and healthy dwellings for both today's climate and future, hotter climates. Comparing two different tools and their methodologies using in-use data is critical to gain confidence in their application at the design stage and to further understand overheating risk, including which dwelling types and rooms are more vulnerable to overheating.

3.4 Introduction

Overheating in buildings is said to occur when the heat built up within a dwelling cannot be easily rejected or removed (ZCH, 2015d). Elevated solar and internal gains are often implicated as causal mechanisms, especially when combined with lowered ventilation rates

(ZCH, 2015b), although other factors such as humidity or occupant behaviour also play a role (CIBSE, 2013).

The Zero Carbon Hub (ZCH) defines overheating as "*the phenomenon of excessive and prolonged high temperatures in the home, resulting from internal or external heat gains, which may have adverse effects on the comfort, health or productivity of the occupants*" (ZCH, 2015d). However, the effect of high internal temperatures on occupants is more complex and this can partially explain why overheating is poorly understood especially in homes (CIBSE, 2013, ZCH, 2015b). Nonetheless, temperature standards now exist that allow a primary assessment of overheating risk. Given the expected rise in temperatures due to climate change and the mitigation-driven imperative for low-energy homes, there is an urgent need to assess whether homes built to higher energy efficiency standards overheat because of high levels of insulation and low levels of air permeability.

3.5 Building design and overheating risk

Overheating risk is not limited to highly insulated airtight new buildings. A national survey of the existing stock found overheating in bedrooms and living rooms, with newer homes (post 1990) at a greater risk (Beizaee et al., 2013). The ZCH found 70% of the housing provider organisations who responded to their survey, experienced an overheating issue within their wider stock and homes with the highest risk were identified as single aspect high rise flats in dense urban locations facing south (Gul et al., 2012, ZCH, 2015d, AECOM, 2012b, ZCH, 2015e, NHBC, 2012c).

Building simulation studies have shown that improving insulation does not increase overheating risk, given "good" design; i.e. appropriate solar shading and ventilation, especially at night (e.g. comprehensive work in (Fosas et al., 2018). Indeed, these studies suggest that increasing insulation can assist in reducing overheating. Other risk factors, such as building type, building services, and occupant behaviour are identified and considered relevant (Porritt et al., 2012, McLeod et al., 2013, Gupta, 2013, Taylor et al., 2014, Gupta, 2015, CIBSE, 2005).

Studies that have monitored indoor conditions, show that some homes do seem to be overheating. However, establishing causality has proven difficult with evidence seemingly pointing in both directions with respect to the effect of increased insulation.

For example, some post occupancy research has suggested that overheating risk *is* influenced increases in insulation levels and air tightness (Sameni et al., 2015, McGill et al., 2017b, Kotol et al., 2014, Beizaee et al., 2013, ZCH, 2015c), though this is exacerbated by occupant behaviour, low ventilation rates and lack of shading devices.

At the same time, counter examples exist: lack of roof insulation is a common cause of overheating in older properties (NHBC, 2012c) and in the European heatwave of 2003 this omission was specifically identified as a risk factor for overheating (Salagnac, 2007). The Building Performance Evaluation project of 76 homes drew inconclusive results as to whether homes with higher insulation levels were more at risk: individual instances of overheating were found but robust conclusions could not be drawn (Palmer et al., 2016). Where overheating does occur, it can often be mitigated through occupant behaviour: The NHBC's report of 4 Passivhaus dwellings found that initially the overheating experienced, by about half the occupants, was reduced once actions were taken to counter this e.g. using external blinds, night-time ventilation and using the summer bypass on the Mechanical Ventilation with Heat Recovery (MVHR) (NHBC, 2012a). Hence, a direct relationship between a higher performing building envelope and overheating risk may not exist. However, what is becoming clear is some new homes are overheating and it is important to identify and address the risk factors.

A summary of the causes of overheating identified in the literature, grouped by three factors: design, building services and occupant behaviour is given below (GHA, 2014, NHBC, 2012c, ZCH, 2015d, AECOM, 2012b).

3.5.1 Dwelling Design and Location

- Orientation and solar gain, in particular, large areas of south/west/east facing glazing
- Window opening limited for reasons of noise, security, outdoor air quality or insects
- Limited or no cross ventilation, especially night-time ventilation
- Lack of, or poorly placed external shading
- Building micro-environment, the heat island effect and lack of mitigation through planting.
- Increases in insulation and air tightness resulting in more heat being retained in the building. Internal insulation impacts on overheating more than external insulation. However, rooms located under uninsulated roofs are also identified as at risk of overheating in contradiction to above.
- Top floor flats are prone to overheating
- Buildings in the South and South East England are more at risk

3.5.2 Building Services

- Summer bypass not present or not activated in MVHR systems
- Heat losses from internal heating, hot water, and solar hot water pipework in both individual and communal systems
- Additional electrical demand and internal gains from building services e.g. pumps

3.5.3 Occupant Behaviour

- Limited window opening and night ventilation
- High plug loads from appliances leading to higher internal gains
- Nonoperation of shading devices
- Number of occupants and occupancy patterns

In summary, certain building types and aspects are potentially more at risk of overheating and poorly specified or installed building services can exacerbate risk. Ensuring building users are aware of and can ventilate their homes, especially at night, is critical to remove any heat built up during the day. However, prior to identifying causality, the more basic question of the actual extent of overheating in highly insulated real dwellings needs investigation, a gap we address in this paper.

3.6 Overheating and health

While increasing levels of energy efficiency will positively impact on preventing excess winter deaths (Guertler and Smith), increased external temperatures associated with climate change, coupled with a drive for more highly insulated and airtight homes, could result in additional health risks associated with summer overheating. High internal temperatures have an adverse effect on health, through stress, anxiety, and sleep deprivation, which can increase mortality (CIBSE, 2017). In the current UK climate, it is estimated there are on average 800 summer heat related deaths each year compared to 25,000 excess winter deaths (Donaldson et al., 2001, FOE, 2011). Therefore, the focus on reducing winter deaths is still the highest priority, however it is important not to solve one problem and create another and, without action, summer heat related deaths could rise. The 2003 heatwave resulted in an estimated 70,000 excess deaths across Europe including 2,000 additional deaths in the UK, mainly amongst older people. In the south of England, excess summer deaths increased by 42% (ONS, 2005, Salagnac, 2007, Robine et al., 2008, Johnson et al., 2005). During that period, UK summer temperatures were 2°C above the 1961-1990 average. It is estimated that mean summer temperatures will rise in the South East of England by 2°C by 2040's (based on medium emissions predictions) and potentially up to 5.4°C by 2070 based on a high emissions scenario (Met Office, 2018).Therefore these higher summer temperatures will not just become more frequent, they will become the norm and by the mid-century, half the summers are predicted to be as warm as 2003 and 2018 (DEFRA, 2009, Met Office, 2018), potentially raising summer heat related deaths to 5,000 per year (AECOM, 2012b).

In dwellings, bedroom temperatures are considered more critical as high internal temperatures affect sleep quality, which in turn impact on both comfort and health of the occupant, through an increase in accidents or atypical behaviour (AECOM, 2012a). CIBSE Guide A advises maximum indoor operative temperatures of 25°C for living rooms and 23°C for bedrooms, as sleep can be impaired above 24°C. Bedroom temperatures should not exceed 26°C unless a ceiling fan is available (Butcher and Craig, 2015).

Therefore, dwellings being constructed today need to be designed to not only manage overheating risk now but also be resilient to predicted increases in external temperatures, with a focus on internal temperatures in bedrooms as this room has the biggest impact on health and wellbeing.

3.7 Passivhaus

Passivhaus is the world's leading and fastest growing standard for low energy buildings with over 65,000 buildings certified worldwide and 1,000 buildings in the UK (PHT, 2018a). The Passivhaus energy standard is designed to deliver highly insulated and airtight comfortable buildings with a space heating demand so low that it can be provided through the ventilation system alone, obviating the need for a conventional heating system. The maximum permitted space heating demand in a European climate is $\leq 15 kWhm^2a^{-1}$ or a heating load $\leq 10 Wm^2a^{-1}$. In addition, there are absolute limits for air permeability, primary energy use and overheating risk. Passivhaus is a demanding energy standard which can be applied to both domestic and non-domestic buildings (Feist et al., 2015b), and is designed and delivered using the Passivhaus Planning Package (PHPP).

A Passivhaus is also designed for thermal comfort in winter and summer. Indeed, the genesis of the standard is in the determination of the minimum energy needed to provide the highest quality indoor environment. Summer interior temperatures are influenced by external climate, window size, orientation and shading, internal gains, and ventilation rates. To meet the Passivhaus overheating standard, internal temperatures should not rise above 25°C for more than 10% of annual occupied hours. Domestic dwellings are assumed to be occupied 100% of the year for certification purposes (annual hours 8,760), therefore no more than 876 hours per year can be above 25°C. Table 13 gives a summary of the assessment of frequency of overheating and the recommendations by the Passive House Institute to ensure good summer internal comfort (Feist et al., 2015b). For Passivhaus certification, summer comfort must be 'acceptable' or better (5-10%), but less than 5% is now considered best practice with some designers aiming for 0% (PHT, 2016).

h>25ºC	Assessment
>15%	Catastrophic
10 -15%	Poor
5-10%	Acceptable
2-5%	Good
0-2%	Excellent

Table 13: Summary of overheating risk criteria

The overheating risk is calculated within PHPP at design stage using the "Summer" worksheet and is applied across the building as whole. The assessment of individual rooms is only recommended in large buildings (usually non-domestic). Critical rooms can be identified within a design and, for example, shading can be added to windows, or night-time ventilation increased, until the frequency of overheating risk for the whole dwelling within PHPP is acceptable (Feist et al., 2015b).

There are limitations with this whole house approach. There may be overall compliance for the dwelling while individual rooms could still be uncomfortable. This methodology also means that different standards cannot be applied to individual rooms e.g. bedrooms where the health impact of overheating is known to be greater. Emerging good practice guidance in Passivhaus design advises on limiting ventilation assumptions through window opening and night time cooling in PHPP at the design stage and minimising user operated shading when possible to reduce overheating risk in operation (WARM, 2012). This supports the research findings, which identified limited use awareness of actions needed to reduce internal temperatures as a risk factor for overheating (Gupta and Kapsali, 2015, AECOM, 2012b, NHBC, 2012c, NHBC, 2012a).

Post occupancy research in the UK

There have been several small-scale post occupancy evaluations of Passivhaus dwellings, and the overheating findings are summarised in Table 14.

Citation	No of dwellings	Internal temperatures		Overheating Findings
		Summer average	Winter average	
(Innovate UK, 2014e)	1	21.7 °C	21.7 °C	Some summer internal temperatures reached 28°C which were linked to user behaviour. However only 2% of annual hours were over 25°C. Opening windows and cross ventilation helped to reduce overheating.
(Ridley et al., 2014)	2	23.3°C	21.7°C	Summer overheating in some bedrooms and living rooms as measured by both the PH and CIBSE standards, with a high summer overheating risk in one dwelling.
(Ridley et al., 2013, Innovate UK, 2014a)	1	23.6°C	22.4°C	15% of hours where over 25°C in the living room which fails PH standard. CIBSE TM52 standard was not met in the in bedroom. However, occupant survey showed this not to be a problem.
(Ingham, 2014, Innovate UK, 2014c)	14	24°C	19°C	Overheating exacerbated by the lack of summer bypass in MVHR and higher internal gains.
(Innovate UK, 2014d)	1	25.5°C		Summer temperatures reported as being uncomfortable, Passivhaus and ASHRAE overheating standards not met. Bedrooms over 25°C 29% of the time. Lack of night-time cooling and use of boost on MVHR cited as exacerbating overheating.

Citation	No of dwellings	Internal temperatures	Overheating Findings
(Innovate UK, 2014b)	4	Between 20°C and 25°C throughout the year	Summer overheating identified with temperatures over 25°C in bedrooms. Overheating exacerbated by limited summer shading and lack of summer bypass on the MVHR. Uninsulated pipework caused high internal gains in summer.
(Sameni et al., 2015)	25		Short monitoring period over the summer showed temperatures over 25°C between 3% and 99% of hours. Flats overheating more than houses. Analysis suggested overheating linked to user behaviour.

Table 14: Summary of Passivhaus overheating case studies.

The studies show that there are overheating risks identified in some of the monitored dwellings and this risk is more prevalent in bedrooms. The incorrect specification and installation of mechanical services can exacerbate overheating, and occupant understanding of increasing ventilation rates, especially at night is important to reducing internal temperatures, supporting the findings of earlier research. Many of these studies point out that the results of one or two dwellings should not be overstated and suggest the need for a larger scale study.

3.8 Adaptive Comfort, CIBSE TM52 and TM59

Passivhaus assumes a fixed maximum internal temperature (25°C) beyond which overheating is considered a risk. The adaptive model of thermal comfort in free running (i.e. naturally ventilated) buildings connects internal comfort temperatures to the external temperatures. It is based on the premise that higher internal temperatures may be tolerated as external temperatures rise and people adapt to their internal conditions by changing clothing, activity or their surroundings for example opening windows or drawing blinds. Internal comfort temperatures therefore will vary as the outdoor temperature changes, rather than being fixed (CIBSE, 2013). This approach may account for why some of the homes in Table 2 had higher internal temperatures but were still considered acceptable to occupants. It has been recommended by CIBSE that new buildings use the adaptive comfort method described in CIBSE TM52 rather than fixed temperatures to assess overheating risk, as long as adaption is available (e.g. opening windows, flexibility of clothing etc).

3.8.1 CIBSE TM59 Design methodology for the assessment of overheating risk in homes

CIBSE TM59 is an assessment methodology for predicting overheating risk in naturally ventilated and mechanically ventilated domestic dwellings. This combines guidance from CIBSE TM52 *Limits of thermal comfort avoiding overheating risk in European buildings* (aimed primarily at commercial buildings) and CIBSE Guide A which gives limits to bedroom temperatures (CIBSE, 2013, Butcher and Craig, 2015).

CIBSE TM52 describes an adaptive comfort model which is based on two assumptions. (i) how we respond to temperature depends on recent experience and (ii) we can undertake interventions to manage heat e.g. removing layers of clothing or opening windows. Therefore, adaptive comfort is only applicable when occupants have some control of their internal environment, which in a domestic dwelling, unless there are constraints, is generally the case. The criteria of CIBSE TM52 are evaluated against ΔT, defined as:

$$\Delta T = T_{op} - T_{max} \qquad \textit{(Equation 9)}$$

Where

T_{op} is the hourly indoor operative temperature (°C)

T_{max} is the upper limit for Category II buildings in EN15251 (°C), given as:

$$T_{max} = 0.33\, T_{rm} + 21.8 \qquad \textit{(Equation 10)}$$

Where

T_{rm} is the exponentially weighted running mean of daily mean outdoor temperatures (°C):

$$T_{rm} = (T_{od-1} + 0.8\, T_{od-2} + 0.6\, T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2\, T_{od-7})\ /\ 3.8$$

Where

T_{od-n} is the daily mean external temperature of the n^{th} day before the day in question (°C)

CIBSE TM52 contains three criteria which must be met to demonstrate there is no overheating risk at the design stage and is applied to summer months (May to September) only.

Criterion 1. *Hours of exceedance*: which defines the acceptable percentage of hours above T_{max}

$$H_e = \sum \text{h} \,\forall\, \Delta T \geq 1°C$$

The summation is performed over all occupied hours (*h*) as defined for the type of building. H_e should not exceed 3% of occupied hours for the months May to September inclusive.

Criterion 2. *Daily weighted exceedance*: deals with the severity of overheating within any one day, which can be as important as its frequency. The W_e threshold is ≤ 6 per day. Where:

$$W_e = (\sum h_e) \times WF$$
$$= (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$$

And:

$$WF = 0 \,\forall\, \Delta T \leq 0, else\ WF = \Delta T$$
$$h_{ey} = hours\ when\ WF = y$$

Criterion 3. *Upper limit temperature* sets an absolute maximum daily temperature (ΔT ≤ 4K) for a room, beyond which the level of overheating is unacceptable.

CIBSE TM59 refines Criterion 1 for domestic application and adds a separate and additional criterion from CIBSE Guide A for bedrooms as shown in Table 15.

Criterion 1A Living Rooms, kitchens, and bedrooms	Criterion 1B: Bedrooms only
TM52 Criterion 1 is evaluated with summer occupied hours set to the range [09.00, 22:00] for lounges and kitchens (1989 hours per year) and 24 hours for bedroom (3672 hours per year).	To guarantee comfort during the sleeping hours the operative temperature in the bedroom between [22:00, 07:00] shall not exceed 26°C for more than 1% of annual hours (32 hours per year).

Table 15: Criterion for assessing overheating risk in free running domestic buildings CIBSE TM59.

Ideally the TM59 methodology should be applied to all dwellings, though some typologies are identified as being at a greater risk of overheating, and therefore should be prioritised for assessment. These are:

1. Large developments
2. Developments in urban areas, particularly in southern England

3. Blocks of flats
4. Dwellings with high levels of insulation and airtightness
5. Single aspect flats

Passivhaus dwellings would be included in the fourth category and therefore a group of dwellings to be evaluated. Whilst Passivhaus dwellings have MVHR systems, summer natural ventilation (window opening, especially at night) is possible, and even encouraged. Therefore, the adaptive method is valid for summertime use unless there are site specific reasons which restrict window opening.

3.9 Method

Our overall aim is to assess the level of overheating in real Passivhaus dwellings using both the Passivhaus and TM59 indicators. To this end, internal temperature data were collected from 82 certified Passivhaus dwellings in the UK. The Technology Strategy Board (now Innovate UK) undertook an £8 million monitoring project of 76 dwelling types, including 35 Passivhaus as part of the Building Performance Evaluation programme. This data, along with other monitoring programs funded by developers and homeowners' own monitoring has been gathered to form this large cohort of temperature data.

Of the 82 dwellings, 62 (76%) were houses and the remaining flats (24%), though all flats were low rise. All dwellings had data from a living room and some collected bedroom data. Additionally, in limited homes data was collected from kitchens, bathrooms, and dining rooms (see Table 16). Some dwellings were monitored over one year, others for several, but all dwellings have at least one heating and summer season. In total over 2 million hours of temperature data was collected. Table 16 gives a summary of the sites and rooms. It is noteworthy that the CIBSE TM59 criteria use operative temperature (T_{op}) which depends on both air temperature (T_a) and mean radiant temperature (T_m), whereas our data only contain T_a. However, studies have shown that, in practice, the difference between T_a and T_m tend to be small and hence T_a can be taken as a good approximation of T_{op} (Nicol et al., 2012, Walikewitz et al., 2015).

Site	Location in UK	Number of homes with data	Number of dwellings on-site	Dwelling type	Location of internal temperature sensor	Source of data	Sampling interval
Site 1	Southwest	3	3	House	Living rooms only	Monitoring by developer	hourly
Site 2	Southwest	19	20	House	Living rooms only	Monitoring by developer	hourly
Site 3	Southwest	1	1	House	Living room only	Monitoring by owner	hourly
Site 4	East	13	14	6 Flats 7 Houses	Living rooms in all dwellings, one bedroom in two houses and a flat	Innovate UK data	5 minutes
Site 5	Southeast	1	1	House	Living room, kitchen, bathroom, and bedroom	Innovate UK data	5 minutes
Site 6	Southwest	3	18	Flats	Living rooms kitchens and bedrooms	Innovate UK data	5 minutes
Site 7	Wales	2	2	House	Living rooms, kitchens, bathrooms and 2 bedrooms	Innovate UK data	5 minutes
Site 8	Northwest	1	1	House	Dining room, living room bathroom and bedroom	Innovate UK data	5 minutes
Site 9	Southwest	2	3	Flats	Living rooms kitchen and bedrooms	Innovate UK data	5 minutes

Site 10	Northern Ireland	2	5	House	Living rooms, bathrooms, and bedrooms	Innovate UK data	5 minutes
Site 11	Northeast	1	28	House	Living room bathroom and bedroom	Innovate UK data	10 minutes
Site 12	Scotland	4	8	House	Living rooms kitchens and 2 bedrooms	Innovate UK data	5 minutes
Site 13	Midlands	1	1	House	Living room and bedroom	Monitoring by owner	30 minutes
Site 14	Northeast	1	1	House	Living room bathroom and 2 bedrooms	Monitoring by owner	30 minutes
Site 15	Scotland	3	14	House	Living rooms kitchens and 2 bedrooms	Innovate UK data	10 minutes
Site 16	Southeast	25	36	9 Flats 16 Houses	Living rooms only	Monitoring by developer	hourly
Total		82					

Table 16: Summary of sites, dwelling types and rooms monitored.

	Living Room	Bedroom	Kitchen	Bathroom	Total
Number or rooms monitored	82	31	12	9	134

Table 17: Summary of room types with measured internal temperature data.

3.9.1 External temperature data

The data set covered the years 2011 – 2017, all of which were mild to cool summers (Figure 13). Where available, mean hourly external temperature was used from the site-specific monitoring data. When unavailable or insufficient (gaps in data, dates not matching internal temperature data), hourly mean external temperature data was collected from a local weather station from the Centre for Environmental Data Analysis (CEDA) (Met Office, 2006).

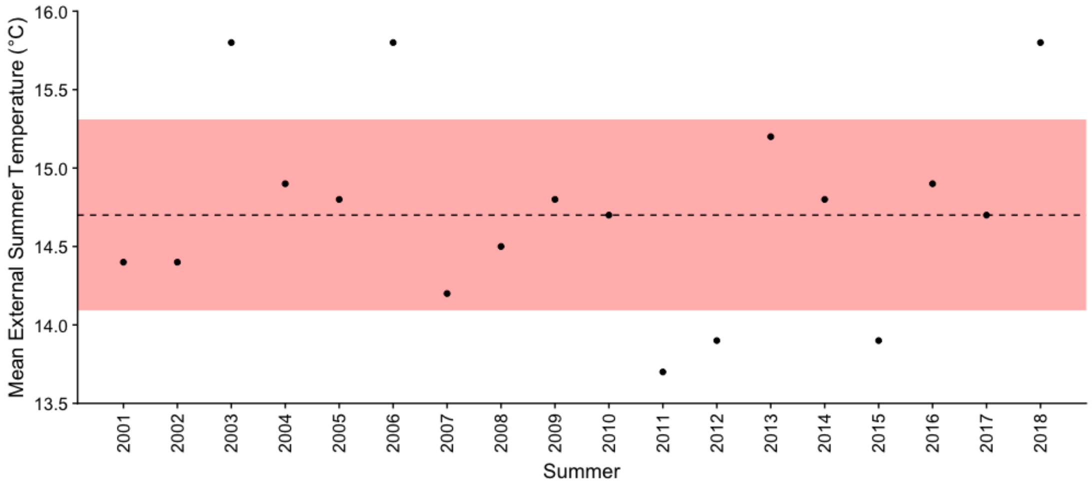

Figure 13: UK summer mean external temperatures between 2001 and 2018. Horizontal line indicates overall mean. The red band indicates 1 standard deviation. Note that the summers of 2011, 2012 and 2015 were cooler than average. Data source: [50]

3.9.2 Application of overheating criteria

The internal and external temperature data were analysed against the two overheating criteria, Passivhaus and CIBSE TM59, discussed earlier. Study specific details are as follows:

(1) Passivhaus: Requires assessment at whole dwelling level. Hence, we report both a whole dwelling mean as well as individual rooms to assess the appropriateness of using the whole dwelling mean. We use both the 10% occupied hours limit (henceforth PH-10%) and the good practice 5% limit (henceforth PH-5%).

(2) CIBSE TM59 Criterion 1A (henceforth TM59-1A):

   a. applies to bedrooms, living rooms and kitchens, therefore any bathroom data was excluded.

   b. where two or more bedrooms were monitored, these are reported separately.

   c. ΔT is rounded per CIBSE TM52 guidance (e.g. ΔT 0.6°C is rounded to1°C).

(3) CIBSE TM59 Criterion 1B (henceforth TM59-1B) applies to bedrooms only. Hence, if there were two bedrooms measured in one dwelling, these are reported separately.

(4) CIBSE TM52 Criterion 2 (TM52-2) and Criterion 3 (TM52-3) are tested to check if they warrant exclusion from TM59.

3.10 Results

Figure 14 shows the mean hourly internal temperatures for each dwelling, separated into summer (May to September) and winter (October to April)[3]. Where only one room was measured in the dwelling this was always a living room, when more than one room in a dwelling was measured this was calculated into a whole dwelling average. Across all dwellings, mean summer temperature internal temperature is 23.0°C and mean winter internal temperature 20.8°C. (~1K higher than the 20°C assumption made at design stage within PHPP for the heating season). Within these averages there is a considerable range of temperatures. Outliers (Q3+1.5*IQR and Q1-1.5*IQR) comprise 2.2% of the total data.

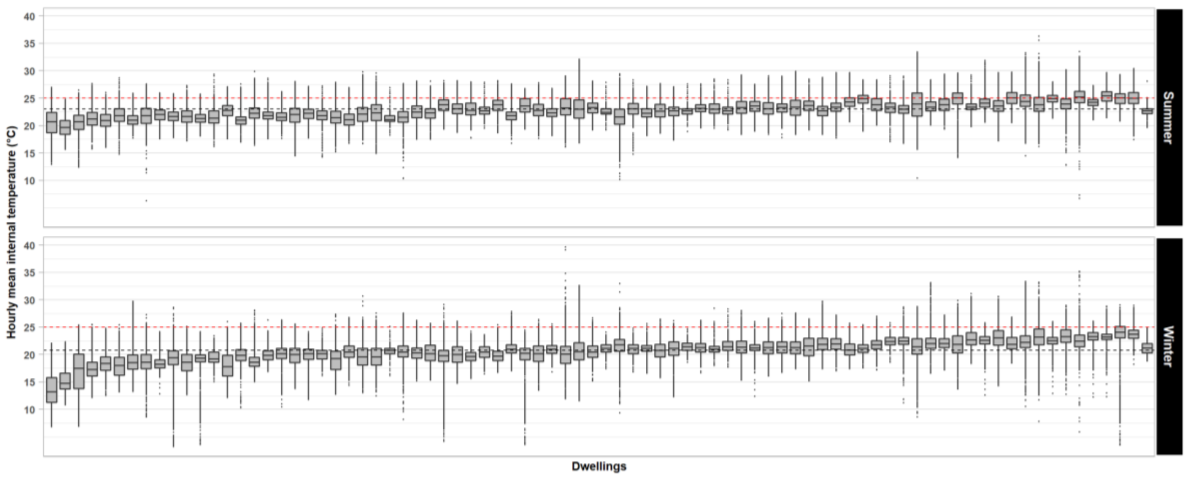

Figure 14: Mean hourly internal measured summer (May to September) and winter temperatures from 82 dwellings. Black dashed line shows mean internal temperatures for summer (23.0°C) and winter (20.8°C). Red dashed line show Passivhaus maximum internal temperature (25ºC).

3.10.1 Passivhaus overheating risk

To certify as a Passivhaus, the overheating risk (number of hours where internal temperatures are predicted to be over 25°C), calculated in PHPP must be less than 10% of occupied hours. Figure 15 shows the percentage hours of exceedance of internal temperatures for all dwellings, separated into houses and flats. Dwellings where internal temperatures exceed 25°C for more than 10% of annual hours are coloured, with the rest in

[3] Note that the Passivhaus standard effectively includes “overheating” in winter as it is computed annually.

grey. Good practice in Passivhaus design now suggests reducing the design overheating risk to 5% of occupied hours, so this more stringent standard is also indicated.

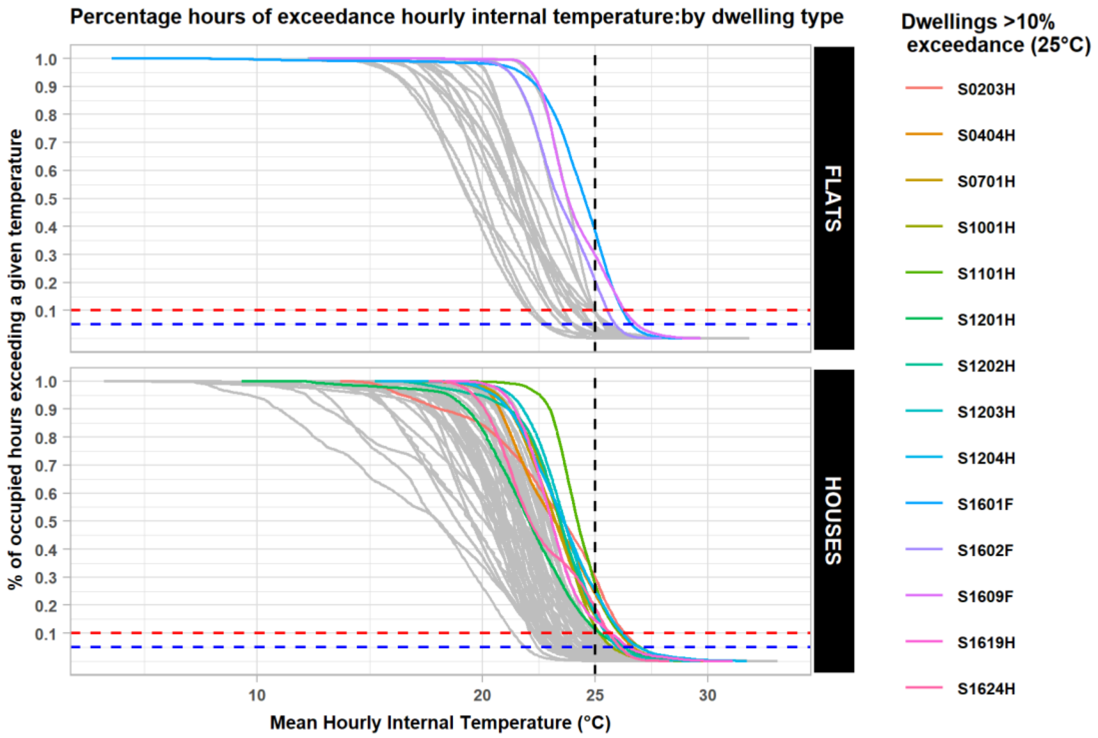

Figure 15: Percentage of occupied hours exceeding a range of internal temperatures by dwelling type. Dashed lines show the intersection of the PH standard 10% exceedance (red), PH good practice 5% exceedance (blue) and 25°C internal temperature (black) thresholds. Each dwelling is referenced by site number (S00), dwelling number and type (H = Houses, F= Flats). Therefore, S0302H is site 03, dwelling 02 and a house. Dwellings with coloured curves exceed the 10% threshold.

14 dwellings (11 houses and 3 flats) have internal temperatures which exceed PH-10%. Hence 82% of houses and 85% of flats meet the standard as shown in Table 18. However, this falls to 65% and 60% respectively, under the PH-5% threshold.

Result Dwelling Type	Number of dwellings	Number of dwellings meeting PH-10%	Number of dwellings meeting PH-5%
Houses only	62	51 (82%)	40 (65%)
Flats only	20	17 (85%)	12 (60%)
Total	82	68 (83%)	52 (63%)

Table 18: Dwellings meeting the Passivhaus standard for overheating risk by type.

While the Passivhaus takes a whole dwelling approach, CIBSE TM59 looks at individual rooms. To allow comparison, PH-10% and PH-5% were applied to individual rooms as shown in Figure 16 with summary data provided in Table 19.

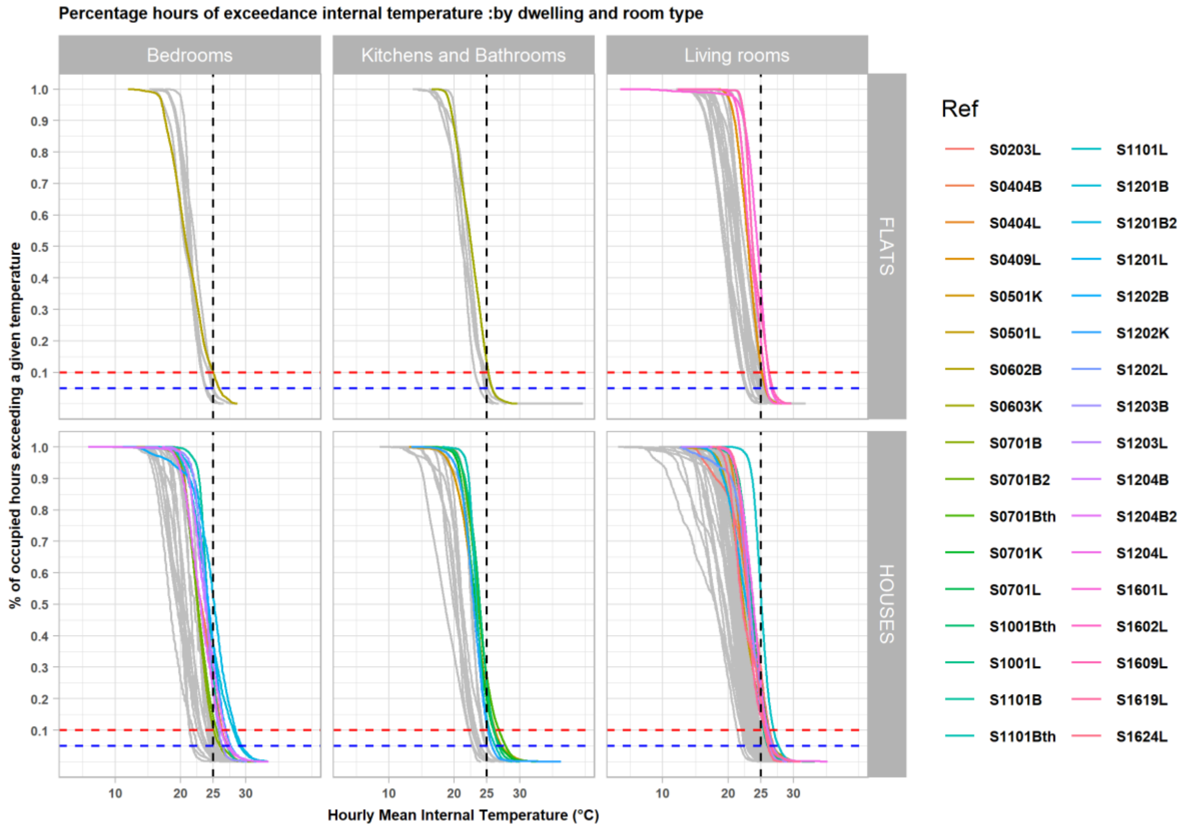

Figure 16: Percentage of occupied hours exceeding a range of internal temperatures by dwelling and room type. Dashed lines show the intersection of the 10% exceedance (red), 5% exceedance (blue) and 25ºC internal temperature thresholds (black). Rooms with coloured curves exceed the 10% threshold.

Our data shows that PH-10% is met in 100 rooms out of 134 (75%) and PH-5% in 80 rooms (60%). Appendix 1 maps these rooms to their dwellings and shows that some homes may meet the whole house standard as specified, with individual rooms exceeding the thresholds. For example, the living room in S0409, the kitchen and living room in S0501, the living room in S0602 and the kitchen in S0603, fail the standard by room but overall these 4 dwellings met the whole house Passivhaus standard. Some problems apply to most rooms on a site, e.g., site 12 (SO1201- S1204) where 11 out of the 12 rooms monitored failed to meet the standard. This site was known to have an issue with uninsulated service pipework including the solar thermal installation which caused high heat gains in the summer and is likely to have contributed significantly to overheating.

Table 19 shows the percentage of living rooms and bedrooms which met PH-10% standard and the enhanced PH-5% standard. Fewer bedrooms in houses (60%) are meeting PH-10%

compared to other rooms (80% and 63%). In the flats a similar percentage of all room types meet the standard (80% and 83%). In total 75% of individual rooms meet PH-10%, reducing to 60% under PH-5%.

Result by Dwelling and Room type	Total number of dwellings / rooms	Percentage dwellings / rooms meeting PH-10%	Percentage dwellings / rooms meeting PH-5%
HOUSES	62	82%	65%
Living rooms	62	80%	63%
Bedrooms	25	60%	56%
Kitchens and bathrooms	16	63%	63%
FLATS	20	85%	60%
Living rooms	20	80%	55%
Bedrooms	6	83%	67%
*Kitchens	5	80%	40%
Total Rooms	134	75%	60%

Table 19: Summary of dwellings and rooms meeting the 10% recommended Passivhaus standard and the 5% good practice thresholds. * Note: No bathrooms were monitored in the flats.

Four instances were found where the whole dwelling met PH-5%, but individual rooms did not (S04:09L, S05:01L, S09:02K, and S15:02L).

3.10.2 CIBSE TM59

In total 124 rooms (i.e. excluding bathrooms) from 82 dwellings were analysed against TM59-1A, shown in Figure 17 and Table 20.

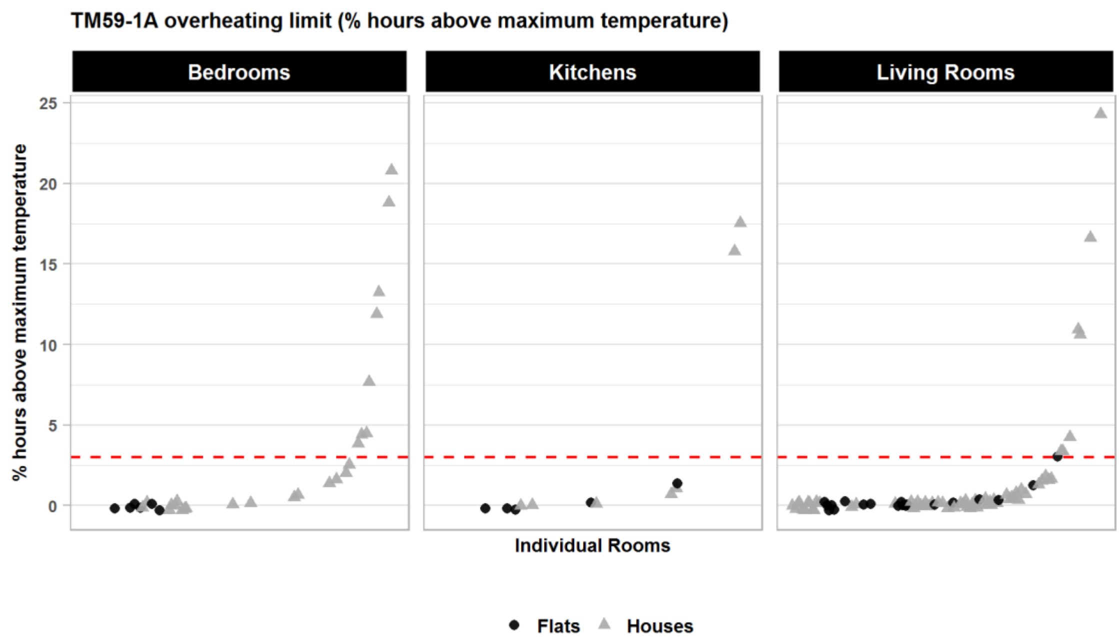

Figure 17: Percent of hours above maximum temperature (T_{max}) as defined by TM59 -1A, split by dwelling and room types. Red dashed line shows the recommended threshold (3%).

Dwelling type	Number of rooms measured	Number of rooms meeting TM59-1A
Flats	31	31 (100%)
Houses	94	76 (81%)
Total	125	111 (89%)

Table 20: TM59 Criterion 1A percentage of hours over maximum temperature all rooms and dwelling types.

All the rooms in flats and 81% of the rooms in houses meet TM59-1A. Further analysis of the houses found that 89 % of living rooms and 71% of kitchens, and 68% bedrooms met TM59-1A as shown in Table 21. The sample for kitchens is small and therefore fewer conclusions can be drawn, but a trend of overheating risk in bedrooms can be seen and this is further analysed below using TM59-1B.

Dwelling type	Room	Number of rooms measured	Number of rooms meeting TM59-1A
Houses	Living rooms	62	55 (89%)
	Bedrooms	25	17 (68%)
	Kitchens	7	5 (71%)
	Total	94	77 (82%)

Table 21: TM59-1A percentage of hours above maximum temperature. Houses only.

Linking T_{max} to the running mean external temperature means potentially higher internal comfort temperatures. Figure 18 shows that mean $T_{max.}$ is between 1-2 °C higher than 25°C for all sites, at 26.5°C for houses and 26.9°C for flats.

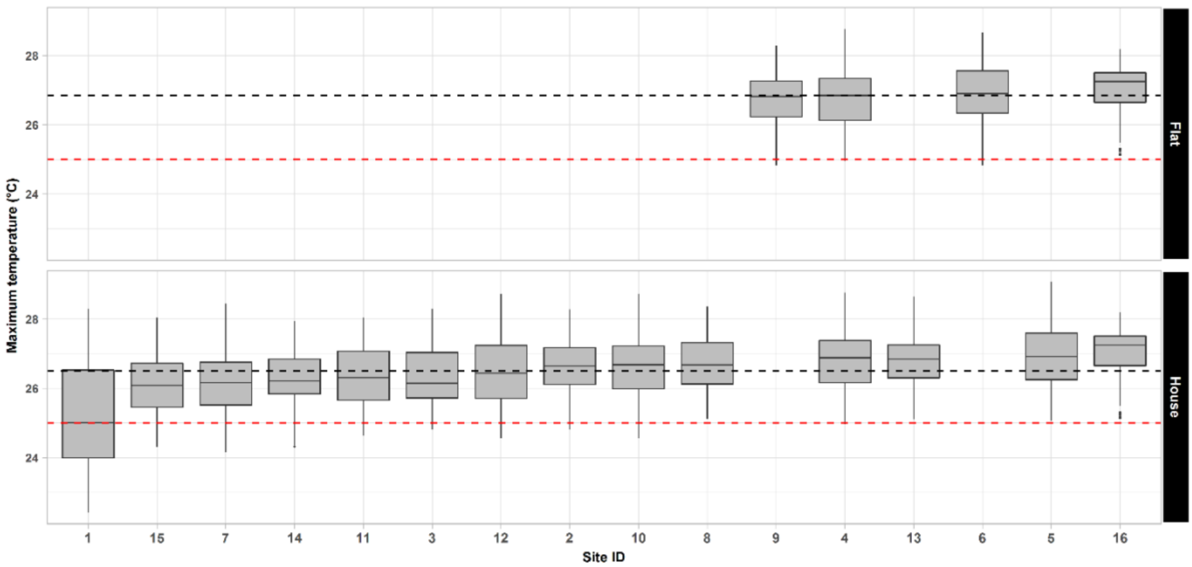

Figure 18: Box and whisker plot of T_{max} computed for TM59 per site, rank ordered by median. The red dashed line shows the Passivhaus 25°C maximum and the black dashed line the means for flats (26.9°C) and houses (26.5°C).

TM59-1B requires all bedrooms to have an internal temperature of less than 26°C for 1% of all night-time hours (between 22.00pm and 07.00am). The results are shown in Figure 19 and Table 22. Seven dwellings on 3 sites had more than one bedroom monitored and these are reported as a separate bedroom (B2). The results show that only 45% of the 31 bedrooms meet TM59-1B. As before, all the bedrooms on-site 12 (S1201 – S1204) failed to meet the standard. Within the houses and flats, both dwelling types show a similar overheating risk in bedrooms, though the flat sample size is too small to draw wider conclusions.

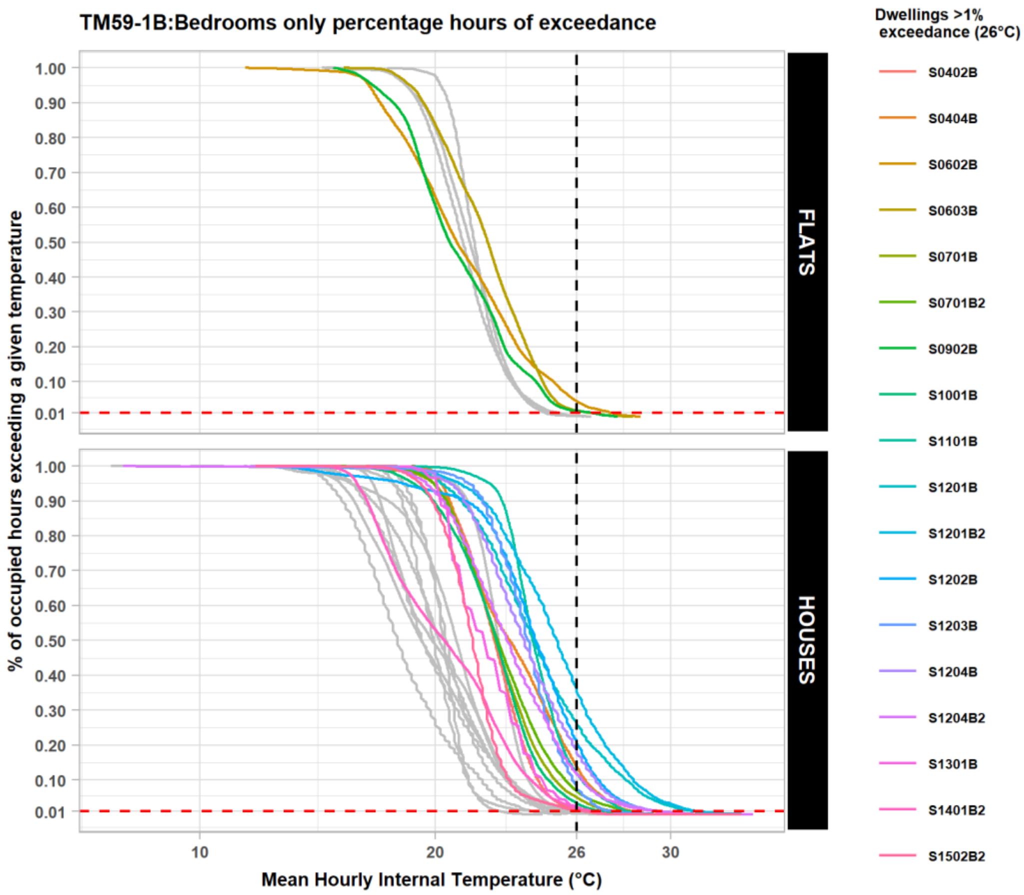

Figure 19 Percentage of occupied night-time hours ∈ [22:00, 07:00] exceeding a range of internal temperatures in bedrooms. Dashed lines show TM59-1B threshold 1% percent of hours (red) and the 26°C limit (black).

Type of dwelling	**Number of bedrooms measured**	**Number of rooms meeting TM59-1B**	**Percent rooms meeting TM59-1B**
Houses	25	11	44%
Flats	6	3	50%
Total	31	14	45%

Table 22:TM59-1B percentage of night-time hours above 26°C, bedrooms only, 1 bedroom per dwelling.

3.10.3 Comparison of CIBSE TM59 and Passivhaus

Table 23 compares the percentage of bedrooms and living rooms which meet all four of the standards[4]. Most rooms meet TM59-1A, and this method did not find an overheating risk in the flats. PH-10% identifies more rooms with an overheating risk especially bedrooms in houses. This is further reduced under PH-5%, particularly for living rooms. Of all the rooms

[4] Kitchens and bathrooms are not reported, as these are both smaller samples and less time is spent in these rooms.

measured, bedrooms are showing the greatest risk of overheating and this is specifically demonstrated under TM59-1B where less than half of rooms meet this standard.

Dwelling type	Room	Number of rooms measured	% of rooms meeting Passivhaus standard (10%)	% of rooms meeting Passivhaus standard (5%)	% of rooms meeting CIBSE TM59-1A	% of bedrooms meeting CIBSE TM59-1B
Houses	Living rooms	62	80%	63%	89%	
	Bedrooms	25	60%	56%	68%	44%
Flats	Living rooms	20	80%	55%	100%	
	Bedrooms	6	83%	67%	100%	50%
Total		113	76%	60%	86%	45%

Table 23: Comparison of CIBSE TM59 and Passivhaus overheating risk criteria by room.

3.10.4 TM52 Criteria 2 and 3

Although TM52 criteria 2 and 3 are not mandated within TM59, we include them for completeness and to assess whether they identify incidences of overheating that the other standards discussed heretofore miss. Table 24 identifies the number of rooms which fail to meet these two criteria.

Result by Room type	Total number of rooms	Number of rooms meeting TM52-2	Number of rooms meeting TM52-3
HOUSES	87	51 (58%)	81 (93%)
Living rooms	62	39 (63%)	60 (96%)
Bedrooms	25	12 (48%)	21 (84%)
FLATS	26	22 (85%)	26 (100%)
Living rooms	20	16 (80%)	20 (100%)
Bedrooms	6	6 (100%)	6 (100%)
Total Rooms	113	73 (65%)	107 (100%)

Table 24: Number of flats and houses meeting CIBSE TM52 Criterion 2 and 3.

Table 24 shows that 65% of the total rooms meet CIBSE TM52 Criterion 2, and less rooms in houses (58%) meet this criterion compared to flats (85%). Bedrooms in houses perform the worse, with only 48% complying. More rooms meet CIBSE TM52 Criterion 3, with 100% of rooms in flats meeting this standard and 93% of rooms in houses. This shows that whilst there may be times when rooms are overheating, the periods when the severity of internal temperatures is unacceptable is limited. In terms of the utility of these metrics to TM59, every room that failed TM52 Criterion 3 also failed TM59 Criterion 1A (see Appendix). This would suggest TM52 Criterion 3 adds little new overheating information. On the other hand, although not all homes failing TM52 Criterion 2 failed TM59 Criterion 1A, all homes failing TM52 Criterion 2 failed TM59 Criterion 1B, with one exception (Site 14, House 01, Bedroom 02). This would suggest that if a bedroom fails to meet TM59-1B at design stage modelling, there is likely to be an overheating risk for the whole dwelling.

3.11 Discussion

Both the Passivhaus design standard and CIBSE TM59 provide methodologies for assessing overheating in domestic dwellings. TM59-1A uses adaptive comfort where acceptable internal temperatures rise in relationship with external temperatures, and therefore allows for higher summer comfort temperatures compared to the Passivhaus standard, but with a lower threshold for allowed hours of exceedance. The Passivhaus standard assesses the whole dwelling, over both the summer and heating seasons, while TM59 considers separate rooms and only measures the summer months. TM59-1B applies a separate standard to bedrooms only, to account for a greater impact on health and wellbeing arising from higher bedroom temperatures. While the two assessments approach overheating in different ways, both can be applied to post occupancy data and compared. The following brief observations regarding the relative merits of each method are pertinent here:

- Passivhaus standard:
    - We find that there is little difference between houses and flats with 83% of the dwellings meeting the Passivhaus standard at the whole house level, as prescribed. However, when applied to individual rooms, only 75% of measured rooms meet the standard. Within that group 60% of bedrooms in houses met the standard, with flats faring much better (83%).

- By taking a whole dwelling approach to overheating, the Passivhaus standard does not differentiate between rooms, and bedrooms are identified here as being particularly at risk. Many of the monitoring programs only measured one room (living room temperatures) which may be masking overheating in other rooms. Reducing overheating risk in the whole dwelling should reduce risk in these rooms, but there is no guarantee, and therefore developing a simple room by room approach to assessing risk could help moderate individual hotspots and ensure that comfort temperatures are consistent throughout the dwelling.
- Passivhaus good practice guidance suggests aiming for a lower percentage of hours above 25°C, either at 5% or 0% and to stress test using future climate files and reducing reliance on night-time ventilation to further reduce overheating risk. When compared to this standard, the number of rooms in compliance reduced to 60%; with a greater number of living rooms (in both houses and flats), and bedrooms in flats failing to meet this more stringent standard. Hence, decreasing the compliance level to these lower percentages would be a way of ensuring greater confidence in maintaining comfort temperatures throughout the whole house, especially as summer temperatures increase in the UK. This approach could then be applied using future climate data files, to ensure designs remain robust.
- It is noteworthy that all the Passivhaus dwellings would have been modelled in earlier versions of PHPP: a significant change to the current version (v9) is the treatment of internal gains, which particularly affects smaller dwellings. This change will reduce a reliance on solar gains to achieve space heating demand, which may impact on overheating risk, and therefore dwellings modelled in this later version, may have reduced overheating.

- CIBSE TM59 standard:
  - TM59 only considers overheating in the summer compared to the annual approach of Passivhaus. This may result in some overheating not being identified if it occurs outside of these months. This may particularly be the case in highly insulated homes when overheating can occur in the shoulder seasons.
  - All rooms in flats met TM59-1A, compared to 82% of rooms in houses. Comparison against the results from using the fixed Passivhaus threshold

(see above) suggests that the adaptive threshold of TM59-1A, despite allowing fewer exceedance hours, is easier to pass.

- The strictest metric (i.e. the one with the highest failure rate) was TM59-1B (55%). Any room failing TM59-1B was also likely to fail all the other standards (including Passivhaus), and there was only one instance of a room failing another standard and not failing TM59-1B (PH-5%, S10:02-BR1, see Appendix). Indeed, TM59 appears to be robust against the exclusion of TM52-2 and TM52-3 since every room failing these criteria also failed TM59-1B (except S14:01-BR2).

3.12 Conclusions

This paper addresses an issue of growing concern in many parts of the world as the drive to reduce energy and carbon emissions from buildings to mitigate climate change is often implicated in increasing overheating. High incidences of overheating in dwellings could significantly affect physical health and, in extreme cases, lead to death. However, little systematic analysis in highly insulated buildings has been undertaken at scale. Hence, we undertake overheating analyses on a nationally representative sample of 82 highly insulated Passivhaus dwellings from all over the UK. We use several metrics to assess overheating and our key findings and recommendations can be summarised as follows:

- The current Passivhaus standard of no more than 10% of annual overheating hours to be greater than 25°C is met more frequently at whole-dwelling level (as prescribed) than when the same standard is applied to individual rooms. Hence, a more risk-averse approach to identifying overheating should require compliance at room rather than dwelling level.
- The good practice PH-5% metric produced a failure rate of 44%, with a strong match against TM59-1B, where available (see Discussion). This suggests that where bedroom data is unavailable, the PH-5% metric applied to living room temperatures at design stage, may provide a proxy for identifying overheating risk in bedrooms.
- Where rooms failed, these were predominantly bedrooms. Meeting TM59-1B was more difficult than criterion 1A for both houses and flats. Only 45% of all bedrooms met this standard, and there was less difference between both dwelling types. However, since there was not a one-to-one correspondence between dwellings failing TM59-1A and TM59-1B, the inclusion of both metrics in the standard seems justified.

- In the literature, flats are generally identified as potentially having a greater overheating risk compared to houses, but little evidence for this was found in our data since a similar percentage of flats and houses met the Passivhaus standard. Indeed, application of TM59-1A suggests houses (82%) are less likely to comply than flats (100%). When TM59-1B was applied, both houses and flats were found to have similar risk. The flats were low rise (none above 3 storeys), which may partially account for these results.

Overall, the results for bedrooms are particularly worrying with 55% of all bedrooms failing the TM59-1B standard, given that the summers under consideration were either typical or cool. Impaired ability to sleep can significantly affect both physical and mental health. Hence, we recommend that highly insulated dwellings such as Passivhaus, consider overheating at individual room level, throughout the year, and with particular attention to bedrooms. We also recommend the use of either TM59-1B or the good-practice PH-5% exceedance threshold, instead of the currently used PH-10% threshold to mitigate this risk.

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Data created during this research are openly available for the University of Bath data archive at https://doi.org/dataset created in Pure - upload data - DOI generated.

3.14 Appendices

3.14.1 Appendix 1 summary of results

In the table below, we map various metrics used to assess the homes in our database against each other. Coloured cells identify rooms where the given criteria (in columns) does not apply. Blank (white) cells identify rooms that passed the given criteria, whereas those with an “F” indicate failure. Rooms are coded as follows “L” is Living Room, “B” is Bedroom 1, “B2” is Bedroom 2, “BTH” is Bathroom 1, “BTH2” is Bathroom 2, and “K” is Kitchen.

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
S01	S01:01	House			L						
	S01:02	House			L						
	S01:03	House			L						
S02	S02:01	House		F	L		F			F	
	S02:02	House		F	L		F			F	
	S02:03	House	F		L	F	F	F		F	
	S02:04	House			L					F	
	S02:05	House			L						
	S02:06	House			L					F	
	S02:07	House		F	L		F				
	S02:08	House		F	L		F				
	S02:09	House			L						
	S02:10	House			L						
	S02:11	House		F	L		F			F	
	S02:12	House			L						
	S02:13	House			L						
	S02:14	House			L						
	S02:15	House			L						
	S02:16	House		F	L		F				
	S02:17	House			L						
	S02:18	House			L						
	S02:19	House			L						

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
S03	S03:01	House			L						
S04	S04:01	House		F	L		F				
	S04:02	House			B				F	F	
					L						
	S04:03	House		F	L		F			F	
	S04:04	House	F	F	L	F	F			F	
					B	F	F	F	F	F	
	S04:05	House			L						
	S04:06	House			L						
	S04:07	House			L						
	S04:09	Flat			L	F	F			F	
					B						
	S04:10	Flat			L						
	S04:11	Flat			L						
	S04:12	Flat			L						
	S04:13	Flat			L						
	S04:13	Flat			L						
S05	S05:01	House		F	BTH						
					B						
					K	F	F	F			
					L	F	F	F		F	

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
S06	S06:01	Flat			B						
					K						
					L						
	S06:02	Flat		F	B	F	F		F		
					K		F				
					L		F				
	S06:03	Flat		F	B		F		F		
					K	F	F				
					L		F				
S07	S07:01	House	F	F	L	F	F	F		F	F
					B	F	F		F	F	
					K	F	F	F			
					B2	F	F	F	F	F	F
					BTH	F	F				
	S07:02	House			L						
					B						
					BTH						
					BTH2						
S08	S08:01	House			L						
					B						
					BTH						

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM522	TM523
S09	S09:01	Flat			K						
					B						
					L						
	S09:02	Flat			K		F				
					B				F		
					L						
S10	S10:01	House	F	F	BTH	F	F				
					B		F		F	F	
					L	F	F			F	
	S10:02	House			BTH						
					B		F				
					L						
S11	S11:01	House	F	F	L	F	F	F		F	
					B	F	F	F	F	F	
					BTH	F	F				
S12	S12:01	House	F	F	B	F	F	F	F	F	F
					L	F	F	F		F	
					B2	F	F	F	F	F	F
					K						
	S12:02	House	F	F	B	F	F	F	F	F	
					L	F	F			F	
					K	F	F				

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
	S12:03	House	F	F	B	F	F		F	F	
					L	F	F				
	S12:04	House	F	F	B	F	F	F	F	F	
					B2	F	F	F	F	F	
					L	F	F	F		F	F
S13	S13:01	House			B				F	F	
					L						
S14	S14:01	House			L						
					BTH						
					B						
					B2					F	
S15	S15:01	House			L						
					B						
					B2						
					K						
	S15:02	House			L		F				
					B						
					B2				F		
					K						
	S15:03	House			L						
					B						
					B2						
					K						

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
S16	S16:01	Flat	F	F	L	F	F			F	
	S16:02	Flat	F	F	L	F	F				
	S16:03	Flat		F	L		F				
	S16:04	Flat			L						
	S16:05	Flat			L						
	S16:06	Flat		F	L		F				
	S16:07	Flat			L						
	S16:08	Flat		F	L		F			F	
	S16:09	Flat		F	L	F	F	F		F	
	S16:10	House			L						
	S16:11	House			L						
	S16:12	House			L						
	S16:13	House			L						
	S16:14	House			L						
	S16:15	House			L						
	S16:16	House			L					F	
	S16:17	House			L						
	S16:18	House		F	L		F				
	S16:19	House	F	F	L	F	F			F	
	S16:20	House			L						
	S16:21	House			L						
	S16:22	House		F	L		F			F	
	S16:23	House			L						

Site ID	Dwelling ID	Type	PH 10% Whole House	PH 5% Whole House	Room ID	PH 10% Room	PH 5% Room	TM59 1A	TM59 1B	TM52 2	TM52 3
	S16:24	House	F	F	L	F	F				
	S16:25	House			L						

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3.16 Postscript

This chapter reported on the post-occupancy internal temperature data from 82 certified Passivhaus homes. The temperature data was compared to the PHPP methodology and CIBSE TM59, two assessment methods available for domestic dwellings in the UK. Comparing a large data set over several summers allows for the Passivhaus standard to be tested at scale, rather than on an individual case basis, and an assessment of the delivery of the standard to date can be made.

The findings addressed Research Question 2, in three ways:

1. The results show there is a performance gap between measured internal temperatures and the maximum allowable, using both the PHPP methodology and CIBSE TM59. In particular, bedrooms in both flats and houses are the most at risk of overheating. As higher night-time temperatures impact on sleep, this can have the greatest impact on health and comfort.

2. The two approaches (PHPP and TM59) to overheating risk are different but results are similar. There was a high correlation between the two methods, particularly in bedrooms. If one dwelling failed the whole house best practice PHPP criteria (<5% hours over 25°C), then the bedroom would usually fail TM59 1B. This is particularly useful, as the weakness of the whole house method (PHPP) is that individual rooms cannot be identified. By reducing design overheating risk overall, this can minimise overheating risk in specific rooms.

3. There is a recognition in the UK that designing to a better practice for overheating (<5% of hours over 25°C) in PHPP will reduce overheating risk in-use. This is supported by these results. The key outcome of the research is that the current overheating risk criteria for Passivhaus (10% occupied hours over 25°C) is not sufficient and that designing to 5% is more likely to deliver internal summer comfort in all rooms, both now and for future climates.

The management of overheating risk at design stage needs building models which are able to reliably predict if a building will overheat. PHPP relies on fixed internal temperatures applied to a single zone. This raises the question of whether a steady state model can begin to predict the dynamic and complex interrelationship of temperature, airflow, shading, and user behaviour (Lomas and Porritt, 2017). However, PHPP considers overheating risk for the whole year and assumes constant occupancy, whereas CIBSE TM59 focuses on the summer months only and assumes an occupancy pattern for each element. This approach requires that models predict accurate indoor temperatures for only a small number of hours. For example, for TM59 criterion B, overheating needs to be predicted for only 32 hours over the whole of the year (Roberts et al., 2019). TM59 also uses set occupied hours, which will differ from household to household (Lomas and Porritt, 2017). PHPP assumes the dwelling is occupied all the time, which is simpler.

Creating the accurate conditions to predict overheating risk, either in a static or dynamic model, are considered more complex than space heating demand and have to take into account any zoning within the building, the fine details of shading (site, overhangs, glazing bars, reveals, etc.), as well as the impact of window opening and implementation of shading devices (Roberts et al., 2019, Lomas and Porritt, 2017). In low-energy homes, generally the heating system requires very little input from the user, however the management of overheating could need much greater user impact, which will make building modelling more difficult to replicate. These issues and the more complex inter-relationship of user behaviour and thermal comfort will be discussed in greater detail in Chapter 5.

Chapter 4 UK Passivhaus and the energy performance gap

4.1 Preamble

This chapter analyses POE space heating and internal temperature data from 97 UK-certified Passivhaus dwellings. The purpose is to give an overview of how Passivhaus is being delivered in the field and if there is evidence of the same EPG, typically found in other dwellings. As discussed in Chapter 1, the three main causes of the EPG are the inaccuracies of data input and the limitation of building models, poor build quality on-site and occupant behaviour. This chapter compares in-use data with the PHPP predictions (testing the accuracy of the models and the quality of construction on-site) and uses internal and external temperature normalisation (testing the accuracy of building models and accounting for user behaviour).

This chapter directly addresses Research Question 3*. Using in-use space heating demand as the measure, how do Passivhaus dwellings in the UK perform once occupied compared to the prediction in design models (PHPP)? Can sufficient data from enough dwellings be collected to consider the UK application of the energy standard as a whole rather than on a case by case basis. Are there methods which can be applied to maximise data collection, when there is limited data available and how accurate would this data be compared to typical collection methods such as heat metering*?

This chapter is based on the published paper "*UK Passivhaus and the energy performance gap"*. Here, data was collected from 97 certified Passivhaus homes, which represents a sufficiently large sample for the data to be statistically informative (p 0.13). The sample included the 82 homes reported on in Chapter 3. This gives a robust overview of how the Passivhaus standard is performing in-use in the UK to date. As data was collected from 13 different sites which are geographically dispersed, with different building typologies and tenures, the data set represents a broad overview of how the standard is being delivered, rather than the small-scale forensic reporting from an individual site which has been typical of the research to date. Data from 8 sites and 16 homes came from the Building Performance Evaluation programme, a large-scale POE programme supported by Innovate UK (Palmer et al., 2016). This data is publicly available on the Digital Catapult platform. The remaining data came from a Passivhaus consultancy and individual homes owners.

In order to maximise the number of dwellings included in the research, data was obtained from three sources. (i) direct heat metering of space heating demand, (ii) monthly heat metering data from a district heating system (total heat), (iii) irregular gas meter readings (total heat). Using these data collection techniques required the development of two new adjustments to estimate space heating demand from limited data. By comparing these data collection methods with known data, the accuracy of this can be assessed and the value as a collection vehicle ascertained. Developing low cost and simple methods to estimate space heating demand could increase the low level of POE currently undertaken.

Higher than predicted internal temperature in-use, can show an EPG which could be accounted for using normalisation methods. Here we apply the method developed in Chapter 2 and use a non-site specific PHPP model to estimate the normalisation factor using measured internal and external temperature data. This allowed normalisation to be applied to a greater number of dwellings, as accessing site-specific PHPP assessment was not possible for any of the sites. This gives more accurate data and allows for user preferences (internal temperature in the heating season) to be allowed for in the building model.

As discussed in the introduction and Chapter 2, complexity and cost are barriers to data collection. Developing simplified robust methods could increase the amount of data available which provide vital feedback loops into the design and construction industry.

4.2 Declaration of authorship

Publication status (tick one)									
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Candidate's contribution to the paper (provide details, and also indicate as a percentage)	The author of this thesis has predominantly contributed to the publication by defining the methodology, collecting and collating the data undertaking the data analysis and writing the manuscript. S Natarajan contributed to the development of the paper as whole and specifically adjustment 3 and reviewed the paper before publication. The contribution by each author are as follows Formulation of ideas: R Mitchell (85%) S. Natarajan (15%) Background R Mitchell (90%) S Natarajan (10%) Design of methodology: R Mitchell (85%) S Natarajan (15%) Experimental work: R Mitchell (95%) S Natarajan (5%) Analysis: R Mitchell (80%) S Natarajan 15%) Presentation of data in journal format: R Mitchell (80%) S Natarajan (20%)								
Statement from candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.								
Signed						**Date**			

4.3 Abstract

Homes contribute 22% of UK carbon emissions, 45% of which are primarily for space heating energy. Delivery of highly insulated homes, new build and retrofit, is needed to help meet the UK's 2050 net zero carbon target. Similar policies are being adopted across the developed world to limit rising carbon emissions. Unfortunately, most new, and retrofitted buildings use as much as 250% more energy than predicted by computer models at design stage, the so-called 'energy performance gap'. Although emerging evidence suggests that buildings built to the low-energy Passivhaus standard do not demonstrate such a gap, data are often from small-scale forensic investigations. Here, we present the first large-scale systematic evaluation of this standard in occupied buildings using multi-year data from 97 UK Passivhaus dwellings spread across 13 sites. As frequency and type of data collection varies between sites, we adopt a pessimistic approach to the analysis by systematically over-estimating space heating demand in the presence of uncertain data. Results pooled across multiple years, show that mean observed space heating demand is 10.8 $kWhm^2a^{-1}$ (SD 9.1) with no statistically significant difference against predicted demand of 11.7 $kWhm^2a^{-1}$ ($p = 0.43$, $d = -0.1$). These results provide powerful evidence in favour of the Passivhaus standard as a reliable means of obtaining low-energy and low-carbon buildings and should be seen in the context that the space heating demand of the average UK home is currently about 145 kWhm2a-1 and a new build home about 50 kWhm2a-1.

4.4 Introduction

4.4.1 Performance gap

All buildings constructed to meet a prescribed energy standard or code are at risk of a performance gap, described as the difference between the predicted thermal and energy performance derived from computer simulations and the actual measured building fabric and energy use once the building is occupied (Wingfield et al., 2008, Bell et al., 2010, Gupta and Dantsiou, 2013, de Wilde, 2014). This is because some variations in measured energy performance naturally appear due to differences in household sizes, occupation patterns and chosen internal comfort temperatures (Bell et al., 2010, de Wilde, 2014). Therefore, it would be usual for some buildings to use more energy than predicted, and others less. However emerging research shows that many buildings use more energy than predicted, compared to less , suggesting the presence of a systematic bias in the actual energy performance of buildings compared to design expectations (ZCH, 2014b).

Dwellings use 28% of all UK final energy (BEIS, 2019b), contributing 22% of total emissions by end user (BEIS, 2020b), compared to non-domestic buildings which contribute 12% of total emissions (CCC, 2015). As there is little sign of an abatement in these emissions (BEIS, 2019a, BEIS, 2018), a performance gap in dwellings will have a significant impact on overall energy and emissions reduction targets. Space heating demand typically makes up 66% of total energy use (Palmer and Cooper, 2013), so greater than predicted space heating will impact the overall energy performance of a dwelling more than any other individual end-use. The UK's Zero Carbon Hub concluded that there is clear evidence of an energy performance gap in new dwellings, which is a risk to homeowners, developers, and government (ZCH, 2014). Field testing has shown that fabric heat losses can be between 50%–60% more than design predictions (Gorse et al., 2013, Gorse et al., 2015), and space heating demand typically 100%–150% greater in new build homes (Gupta and Kotopouleas, 2018, Bell et al., 2010). The main identified reasons for this energy performance gap are the quality of the design and building modelling, construction and commissioning, occupancy patterns, user behaviour, and robustness of post occupancy testing (Wingfield et al., 2008, Bell et al., 2010, Stafford et al., 2012, Gupta and Dantsiou, 2013, ZCH, 2014c, Imam et al., 2017, Gupta and Kotopouleas, 2018, Gill et al., 2010).

One of the challenges to understanding the energy performance gap is the lack of post-construction monitoring (ZCH, 2014a). This shortage of performance data means that the building industry does not know if it is delivering on the expected energy standards. At the time of writing, the UK government is consulting on a new Future Homes Standard (MHCLG, 2019), partially designed to address performance gap concerns. However, without a strong evidentiary basis, there is a risk that the energy performance gap may not be eliminated and may even increase (Wingfield et al., 2008, Gorse et al., 2013). Therefore, it is imperative that homes built to today's standards meet design expectations, whilst considering user preferences, to ensure that any improvement in regulation translates into a similar improvement in actual building performance.

4.4.2 Passivhaus

Passivhaus is a demanding energy performance standard for both domestic and non-domestic buildings (Feist et al., 2015b), and is a leading global low-energy building specification. To date, over 65,000 buildings have certified to this standard, including 1,300 in the UK (iPHA, 2020, PHT, 2020a). A Passivhaus is designed to deliver super-insulated and airtight comfortable buildings, that have a space heating demand so low that there is no requirement for a conventional heating system. The low heating loads could be met through a heating element in the mechanical ventilation system alone, without compromising on comfort, though other heating systems are also used.

The maximum permitted annual space heating demand in a European climate is ≤15 $kWhm^2a^{-1}$ or a heating load ≤ $10Wm^2a^{-1}$. In addition, there are minimum requirements for U-values, thermal bridges, air permeability, primary energy use and overheating risk. A summary of the main elements of the Passivhaus standard is given in Table 25Crucially, space heating demand is calculated using Treated Floor Area (TFA), which excludes certain elements such as internal partitions, double height ceilings and any area below 1m in height, e.g. under staircases. As annual space heating demand is divided by TFA, and not total or built floor area, this tends to encourage the maximisation of usable floor area within the building during the design process.

Energy	**Limiting standard**
Space heating demand	≤15 $kWhm^2a^{-1}$
Heat load	≤10 Wm^2a^{-1}
Primary energy demand	≤120 $kWhm^2a^{-1}$
Building fabric	**Limiting standard**
Floor/Walls/Roof	≤0.15 Wm^2K^{-1}
Windows and doors	≤0.8 Wm^2K^{-1}
Air permeability	≤0.6ach_{n50}
Thermal bridges	Zero
Overheating	≤10% occupied hours over 25ºC (internal temperature)

Table 25. Summary of the main elements of the Passivhaus standard.

Designing and demonstrating compliance with the Passivhaus standard is achieved using Passive House Planning Package (PHPP) which was developed by the Passive House Institute (PHI) in 1988 and is based on EN 832 (ISO 13 790). PHPP comprises of a series of interconnected spreadsheets representing steady state monthly heat flow and is used to calculate the annual heat balance, final energy demand and overheating risk. It has been calibrated with dynamic simulation models (DYNBIL) and verified against measured consumption data (PHI, 2007, Feist W, 2001).

Each certified Passivhaus goes through a quality assurance process, through a detailed review of the design and construction, including evidence from site, by an experienced independent certifier. This is to ensure that the building will perform as intended (Feist et al., 2015a).

4.4.3 Passivhaus case studies in the UK

There have been several in-depth case studies of UK-certified Passivhaus homes, typically on individual sites, and often provide a forensic analysis of the performance of the building fabric (summarised in Table 26). The results of post-construction building testing show small variations in heat loss coefficients, in situ U-values, and air permeability, but in general the measured results were close or very close to design predictions (Johnston et al., 2014). As these values are already very low, a small change gives a disproportionally large percentage increase or decrease. To put the results in context, the Leeds Beckett new build co-heating study shows the differences between modelled and measured heat loss in 27 new build non-Passivhaus UK dwellings (Johnston and Siddall, 2016). The average difference between designed and measured performance was +50WK^{-1} (i.e. 50% greater than predicted) with two buildings losing twice as much heat as predicted. When seven certified Passivhaus dwellings were tested using the same methodology, the average difference in heat loss was +6WK^{-1} (7% greater than predicted), with one dwelling losing less heat than predicted (Johnston and Siddall, 2016). As our summary of current studies incorporating Passivhaus dwellings in Table 26 shows, when space heating demand was measured, most UK Passivhaus dwellings (75%) perform *better* than design predictions. Whilst the results from these case studies are illuminating, as Ridley et al state "*Great care must be taken not to overstate the results from single case study houses, only when the monitored performance of several UK Passive House dwellings becomes available will an assessment of their overall performance be possible".* (Ridley et al., 2013 p.68)

Study	No of dwellings	Space Heating demand ($kWhm^{2}a^{-1}$)			Research Findings
		Design (D)	Actual (A)	Δ_{D-A}	
(Johnston and Siddall, 2016)	7	Co-heating testing only			Co-heating testing showed a variation between -10 WK^{-1} and + 8 WK^{-1} (-15% to +21%).
(Innovate UK, 2014e)	1	13	7 (partial data only)	−6	In situ U-value testing showed increase in U-value from 0.09 $Wm^{2}K^{-1}$ to 0.10 $Wm^{2}K^{-1}$ and 0.13 $Wm^{2}K^{-1}$. However measured space heat demand was less than design prediction.
(Ridley et al., 2014, Guerra-Santin et al., 2013)	2	15 17	9 26	−6 +9	In situ testing showed a slight increase in U-value from design 0.095 $Wm^{2}K^{-1}$ to 0.105 $Wm^{2}K^{-1}$ in one dwelling. Increase in heat loss coefficient from 58 WK^{-1} to 62 WK^{-1} and from 37 WK^{-1} to 45 WK^{-1} (+8%, +21%). Air testing met Passivhaus standards. Space heating demand less than predicted in one dwelling and greater in the other.
(Ridley et al., 2013, Innovate UK, 2014a)	1	15	12	−3	Co-heating test below design figure by 15%, heat flux testing in line with design figures. Slight increase in air permeability, some minor faults with building services. Space heating demand less than design predictions.

(Ingham, 2014, Innovate UK, 2014c)	14	Space heating not measured separately			In situ U-value testing showed increase from design 0.09 Wm^2K^{-1} to an average of 0.15 Wm^2K^{-1}. Airtightness deteriorated and only five units met the standard after two years.
(Johnston et al., 2014)	3				Mean air leakage rate between 0.66 and 1.30 ach@N50, in situ U-value testing showed no difference in some U-values and an increase from 0.08 to 0.13 Wm^2K^{-1}, co-heating testing showed an increase of between 2 and 7 WK^{-1}.
(Sharpe and Morgan, 2014)	4	13 13 12 12	40 4 9 6	+27 −9 −3 −6	Air permeability increased to between 1.6and 1.9 ach@N50, increase in in situ U-values from 0.10 Wm^2K^{-1} to 0.12 Wm^2K^{-1}. Space heating less than predicted in three units, greater in one.

Table 26. Summary of post-occupancy case studies of UK Passivhaus dwellings.

4.4.4 Large-scale post-occupancy evaluation

The largest reported post-occupancy evaluation from Passivhaus dwellings comes from the EU project CEPHEUS (Cost Effective Passive Houses as European Standards). Set up between 1998 and 2001, this tested the technical feasibility and viability of the Passivhaus standard in Germany, Sweden, Austria, Switzerland, and France. In total, 221 housing units on 14 different sites were constructed and over 100 were monitored.

The average space heating demand across all sites for year one was 19.6 $kWhm^2a^{-1}$ with a standard deviation of 9.9 $kWhm^2a^{-1}$, compared to the design standard of 15 $kWhm^2a^{-1}$. Although this is an increase of 30%, it is from a low baseline and can hence be considered to be a qualified success. At the time, this was an 84% reduction in heating energy demand compared to the building codes, with many of the building components and practices employed being new to industry actors (Feist W, 2001, Schnieders, 2003a).

This project has a large sample of dwellings, however there were time constraints on monitoring and some measured heating data was extrapolated from a partial year. The results showed large differences in space heating consumption, both between the 11 different projects and also among different dwellings on the same site.

Two decades have passed since the CEPHEUS data were collected. Meanwhile, the Passivhaus standard has spread to other countries, such as the UK. At the time of writing, the UK government is also considering the direction in which Parts L and F of the building regulations will evolve, such as through the public consultation on the Future Homes standard (MHCLG, 2019). As both this standard and Passivhaus aim to minimise the energy performance gap, it is timely to undertake an analysis of the performance of Passivhaus homes in the UK. Since space heating is the primary driver of performance, our main aim is to assess whether the observed space heating demand of Passivhaus homes matches their predicted demand at design stage.

4.5 Methods

Our aim is to compare *predicted* and *observed* space heating energy consumption for a sample of Passivhaus homes. There are around 1,300 certified Passivhaus units[5] in the UK, which form the population from which we must draw our sample. A statistical power analysis with typical values for significance[6] (i.e. $\alpha = 0.05$), power[7] (i.e. $\beta = 0.8$) and small effect sizes of between 0.2 to 0.3[8] (Walker, 2010, Cohen, 1992) suggests a sample size of 198 to 90, respectively. A small effect size is appropriate, as the baseline target demand is low for Passivhaus homes (i.e. 15 $kWhm^2a^{-1}$). The population standard deviation is unknown, but if we assume that the mean is the same as the target value of 15 $kWhm^2a^{-1}$, then our assumption of a low effect size suggests differences between predicted and mean demand of between 3 and 4.5 $kWhm^2a^{-1}$ or greater would be termed significant.

Using the above analysis as a guide, we obtained heating and temperature data from 97 UK Passivhaus dwellings through a combination of (i) monitoring programmes by consultants, (ii) publicly available Innovate UK data from the Building Performance Evaluation programme, and (iii) self-reported data from homeowners. This was the maximum number of dwellings available with sufficient data. The main requirement for inclusion in the study was the availability of at least one year's heating data as well as indoor temperatures. Predicted space heating demand was obtained from the Passivhaus certificate for each dwelling. However, as the observed data was spread across multiple sites and collected by different actors, they do not follow a homogenous measurement protocol. Overall, they can be classified into three categories, as shown in Table 27 (further details in Appendix 1). It is clear that dwellings falling into Category A will provide the clearest picture of performance as space heating demand is directly measured, whereas this will need to be inferred from total heating consumption for Categories B and C.

[5] These are not disaggregated by domestic and non-domestic, but the overwhelming majority are known to be domestic.
[6] The probability of returning a Type I error, i.e. a false positive.
[7] The probability of returning a Type II error, i.e. a false negative.
[8] That is, the difference between the predicted and actual space heating demand will differ by at least 0.2 to 0.3 standard deviations.

Category	Dwellings			Years of data	Heat data		Indoor temperature
	Flats	Houses	Total		Type	Frequency	Frequency
A	5	27	32	1–3 years	Separately measured space heating	Varies	5–15 minute
B	4	35	41	3 years	Total heat only	Monthly	n/a
C	12	13	24	2 years	Total heat only	Bi-annual	Hourly

Table 27. Summary of sites and data collection.

Ideally, data should come from metering over at least two years, as the first heating season can show higher demand while the moisture in the building's construction materials dries out and building services are fine-tuned (Feist W, 2001). However, this is not always possible and so the minimum requirement was only for a single heating season of data. It is likely that this will tend to produce higher space heating demand, thus biasing the results against the achievement of the standard and increase the performance gap, but this is consistent with our methodological approach, described further below.

4.5.1 Methodological approach

Given the disparate sources of data and their varying levels of resolution and detail, our overall approach is to be conservative wherever estimates are used. In other words, we systematically over-estimate space heating demand wherever we are uncertain of either modelled or observed data, biasing our results against the achievement of the standard. That is, we undertake a series of adjustments, described further below, that will *inflate* space heating demand, thus making it harder for the dwelling to meet the Passivhaus standard of 15 $kWhm^2a^{-1}$, and potentially creating a greater gap between observations and predictions[9]. The only exception to this is the normalisation process (described in Appendix 3) which is aimed at neutralising bias in model predictions. The adjustments are mapped against the categories of data shown in Table 27 and are described further below.

4.5.2 Adjustment 1

In Category A data (Sites 1–11 in Appendix 1), where space heating demand was separately measured, the following minor adjustments were used to account for any uncertainties in data collection.

[9] It is noteworthy that for dwellings whose observed space heating demand is lower than predicted, such adjustments will tend to push results closer towards predictions. This bias is acceptable as the current problem is primarily to do with observed demand being around two orders of magnitude *higher* than predicted.

- *Internal floor areas*: In some cases, it was uncertain if the reported space heating data was calculated from gross internal floor area as used in the Standard Assessment Procedure (SAP 2012), used to show compliance with Part L1A of UK Building Regulations, or TFA as used in a PHPP assessment. As TFA excludes certain elements such as internal partitions, double height ceilings and any area below 1m in height (e.g. under staircases), TFA is typically 10% lower than gross internal floor area (AECB, 2008). This tends to produce a higher estimate of space heating demand than when using gross floor area. Hence, in our data, if space heating demand was reported by floor area without specific reference to TFA and a PHPP assessment, a reduction of 10% floor area was made and the space heating recalculated. Appendix 6 shows a summary of the TFA for each dwelling.
- *Complex heating and hot water systems*: Site 10 had a wood stove providing heating and hot water. The allocation to space heating was based on the manufacturer's stated percentages.
- *Distribution losses*: No allowance was made for distribution losses as individual heating systems were located within the thermal envelope and therefore these losses would provide useful heat in winter.

4.5.3 Adjustment 2

Here, we look at Category B data with combined space heating and hot water demand from a heat meter within each property. All of these come from Site 12 (Appendix 1). Hence, a method is needed to separate weather and non-weather loads (hot water use).

A simple method would be to use summer loads (when it is assumed there are no heating degree days), as an indicator of hot water use and extrapolate to calculate annual hot water demand. This is then deducted from total heat to estimate annual space heating (CIBSE, 2006, Gill et al., 2011, Peper, 2017). This method is based on two assumptions: (i) That summer heat consumption is for hot water only, and (ii) that hot water use is consistent throughout the year with no marked differences between summer and winter use.

In highly insulated, airtight homes, there can be more confidence in the first assumption, and this can be tested using measure space heating data from low-energy dwellings. Figure 20 shows the monthly measured space heating demand from two sources: 10 Passivhaus[10] and 18 low-energy homes (Code for Sustainable Homes[11] (CSH) level 5 and 6 dwellings), representing 61 winter and summer seasons. There is little or no space heating demand

[10] Of the 32 in Category A, only 10 had monthly metered space heating.
[11] A low energy homes standard developed in the UK but now largely abandoned.

recorded in June, July, and August, and Table 28 gives the percentage of monthly total heat that is space heating demand from the measured data. Therefore, it is reasonable to infer that heat demand for these months is for hot water loads only.

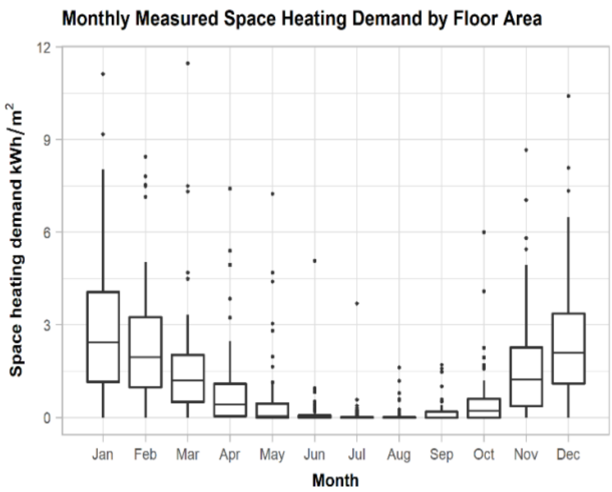

Figure 20. Measured monthly space heating demand from 10 Passivhaus and 18 Code for Sustainable Homes (Level 5 and 6) dwellings.

From this, the percentage of annual space heating demand used each month was calculated (See Table 28).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Percentage	20%	18%	12%	6%	3%	1%	0	0	3%	7%	12%	18%

Table 28. The percentage of annual space heating demand typically used each month.

The second assumption is that monthly hot water loads are consistent over the year. Literature from field tests suggests that hot water consumption reduces in July and August, the “summer slump” which could be attributed to occupants taking summer holidays or having cooler baths and showers (Energy Savings Trust, 2008) and could result in an underestimate of annual hot water use (Peper, 2017).

Standard Assessment Procedure[12] (SAP, version 2012) methodology includes a reduction in hot water consumption in the summer months and achieves this by applying different monthly factors, base on in-use data, to average hot water use across the year, as shown in Table 29 below (BRE, 2013c)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Factor	1.1	1.06	1.02	0.98	0.94	0.90	0.90	0.94	0.98	1.02	1.06	1.10

Table 29. SAP 2012 monthly factor for hot water use.

[12] The UK’s national calculation methodology, compliant with the European Performance of Buildings Directive, that allows a standardised comparison of the energy and environmental performance of dwellings.

Since SAP applies to a wide range of dwelling performance categories, it would be naïve to assume the same factors also apply in super low-energy buildings such as Passivhaus. Hence, we test this assumption using measured hot water data from the same low-energy dwellings as before (excluding three further units[13]). Figure 21 shows the mean monthly summer (defined as June, July, and August) hot water use compared to the mean monthly hot water use for rest of the year.

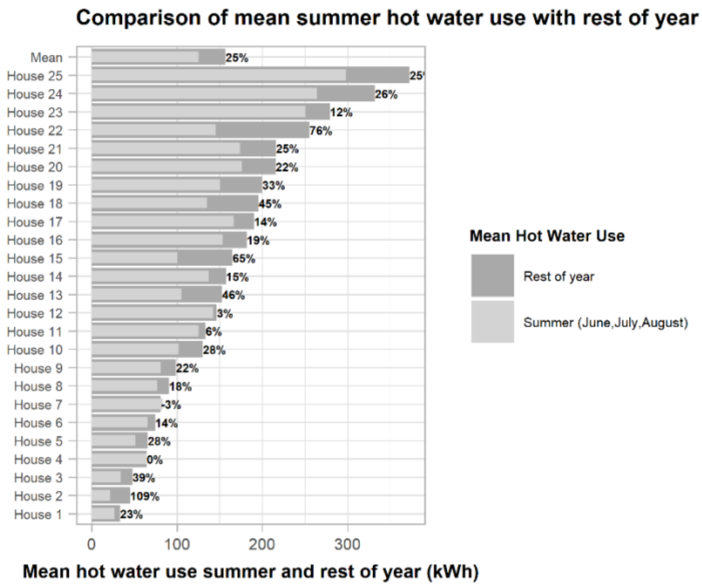

Figure 21. Comparison of mean summer hot water use compared to the rest of the year from 7 Passivhaus and 18 Code for Sustainable Homes (Level 5 and 6) dwellings.

The figure shows that with the exception of houses 4 and 7, all the dwellings used more hot water on average in the winter months compared to the summer, with a mean difference of 25%. Therefore, to assume mean monthly summer hot water use represents average monthly hot water use for the rest of the year would be incorrect. In general, the simple approach would underestimate annual hot water demand and therefore significantly, and unrealistically, overestimate annual space heating demand.

Using the monthly hot water data from these 25 dwellings, a monthly factor was calculated in line with the approach used in SAP (2012) and the equation to do this is shown below.

$$Monthly\ factor = (Annual\ hot\ water_{\ measured}/12)/Monthly\ hot\ water_{measured} \qquad \text{(Equation 11)}$$

Figure 22 shows a boxplot of the monthly measured factors from the 25 dwellings with a line of best fit, compared to the SAP (2012) hot water factors given in Table 29. The SAP (2012)

[13] Hot water data was mixed with a solar thermal installation making it hard to disaggregate.

hot water factors and measured factors have some differences, with the measured factors showing lower hot water use in summer compared to the SAP.

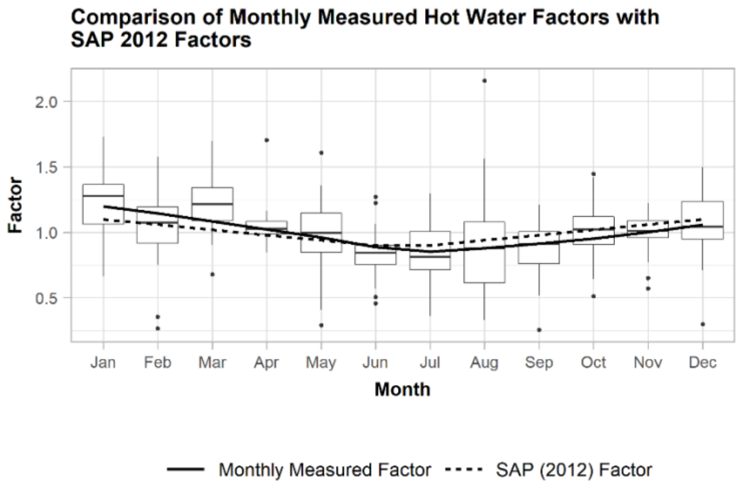

Figure 22. Comparison of monthly measured hot water factors (indicated by the solid line) and SAP (2012) hot water factors (indicated by dashed line).

Table 30 below gives a comparison of the calculated hot water factors compare to SAP (2012) hot water factors

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
SAP 2012 Factor	1.10	1.06	1.02	0.98	0.94	0.90	0.90	0.94	0.98	1.02	1.06	1.10
Measured factor	1.20	1.14	1.08	1.02	0.96	0.89	0.85	0.88	0.91	0.95	1.00	1.06

Table 30.SAP 2012 hot water factors compared to the monthly measured hot water factors from 26 low energy homes

The measured factors show a larger “summer slump” which would result in a higher estimation of hot water use and a subsequent lower space heating demand. In line with the cautious approach, the SAP factors were applied to the measured Category 2 data to estimate annual hot water use. This approach uses summer total heat meter readings and the method described in Table 31.

Step	Variable to compute	Explanation
Step 1	$Hot\ water_{\ June-August}$	measured total heat (kWh) June, July, and August
Step 2	$Hot\ water_{\ SAP\ uplift}$	$\sum \frac{Hot\ water_{\ June}}{0.9} + \frac{Hot\ water_{\ July}}{0.9} + \frac{Hot\ water_{August}}{0.94}$
Step 3	$Hot\ water_{\ \ baseline}$	$\frac{Hot\ water_{\ SAP\ uplift}}{3}$
Step 4	$Hot\ water_{\ \ Monthly}$	$(Hot\ water_{\ baseline})\ x\ SAP\ hot\ water\ factors$
Step 5	$Hot\ water_{\ \ Annual}$	$\sum Hot\ water_{\ \ Monthly}$
Step 6	$Annual_{\ \ Total\ heat}$	$\sum Total\ heat_{\ \ Monthly}$
Step 7	$Space\ heating_{\ Annual}$	$Annual_{Total\ heat} - Hot\ water_{\ Annual}$

Table 31. Adjustment 2: calculation of annual space heating demand using estimated hot water use from summer heat.

As all the dwellings were single units and heat metered at the point of entry to the home, no additional calculations were made for distribution losses or boiler efficiency (Peper, 2017).

4.5.4 Adjustment 3

This adjustment applies to data with the lowest temporal resolution, i.e. Category C. All the dwellings in this category are drawn from Site 13 (Appendix 1). Twice yearly gas meter readings were taken, once in late spring/summer and the second in early autumn. A table of meter reading dates is given in Appendix 2.

The simple approach would be to apply adjustment 2 described above. However, some summer meter reading dates included both the key summer months (June, July, and August), and additional months where there could be some space heating demand. For example, some readings were taken early in spring and included March and April which could include some space heating demand (e.g. in Figure 20 above). Therefore, if hot water use was estimated from this data using adjustment 2, there is a risk of an *over*estimation of summer hot water use and a subsequent *under*estimation of space heating demand in the winter heating season. This is contrary to the cautious approach. Therefore, a further adjustment was developed to extract space heating demand from total annual hot water use.

Step	Variable to compute	Explanation
Step 1	$Total\ heat\ _{Annual}$	There are two years of Category 3 data (see Appendix 2). Year 1 meter readings start on 31 August and for each dwelling there are meter readings for between 378 and 402 days. Year 2 meter readings contain between 336 and 380 days, and 83% of dwellings have a full year or more of data. If no adjustments are made, for Year 1 there will be an overestimation of total energy use. For Year 2, two dwellings are 29 days short of a complete year and two dwellings 18 days short. Therefore Year 1 data was pro-rata and excess days added to Year 2 to create two sets of data of 365 days.
Step 2	$Total\ heat\ _{Monthly\ ratios}$	Using the combined space heating and hot water data from the 25 low-energy homes in Figure 20 plus the three years Category 2 data (a further 39 homes) annual total heat for each dwelling was calculated. From this the percentage of monthly total heat to annual total heat is calculated (see Figure 23)
Step 3	$Hot\ water\ _{Summer}$	From Table 39 Appendix 5, we observe that for June, July, and August typically 5%, 4.4% and 4.4% of total heat is used. Using the same principle as Adjustment 2, we can assume this represents hot water use only and calculate the average over the three months to estimate summer hot water use. Then the SAP factors are applied to estimate annual hot water use, which is taken from the total heat annual reading to estimate annual space heating demand. Finally, this is adjusted to take boiler efficiency into account.

Table 32. Adjustment 2 steps 1–3.

Figure 23 shows the monthly proportion of total heat, with a smooth line.

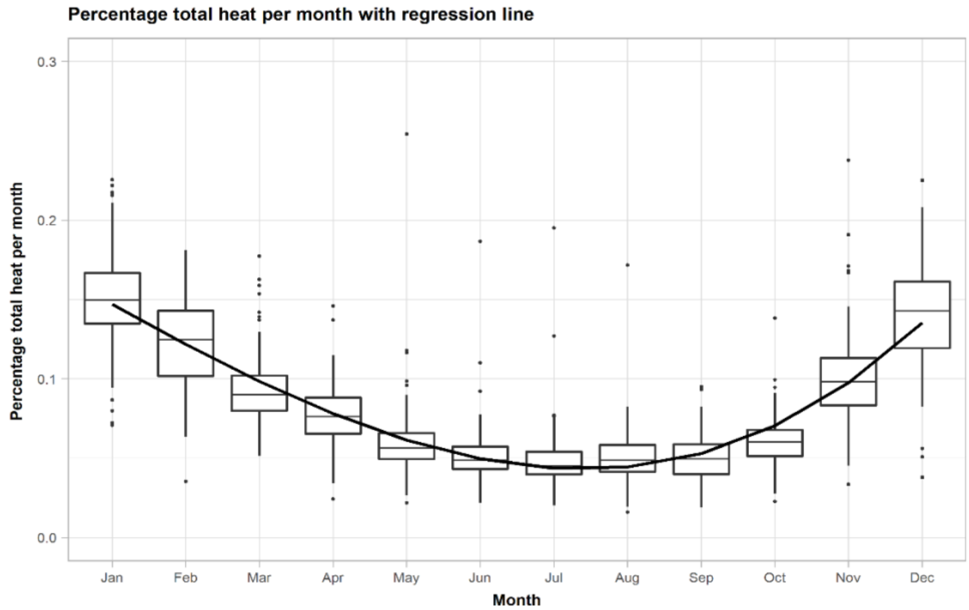

Figure 23. Percentage of monthly total heat from 64 Passivhaus and low-energy homes.

Using the principles of steps 1–3 the following are then calculated.

Step	Variable to compute	Explanation
Step 1	$Annual_{Total\ heat}$	meter readings – see table above
Step 2	$Hot\ water_{Summer}$	$Annual_{Total\ heat}{}^{*} \sum (Monthly\ percentages\ June,\ July,\ and\ August\ from\ Table\ 39)$
Step 3	$Hot\ water_{SAP\ uplift}$	$\sum \frac{Hot\ water_{June}}{0.9} + \frac{Hot\ water_{July}}{0.9} + \frac{Hot\ water_{August}}{0.94}$
Step 4	$Hot\ water_{baseline}$	$\frac{Hot\ water_{SAP\ uplift}}{3}$
Step 5	$Hot\ water_{Monthly}$	$(Hot\ water_{baseline})\ x\ SAP\ hot\ water\ factors$
Step 6	$Hot\ water_{Annual}$	$\sum Hot\ water_{Monthly}$
Step 7	$Annual_{Total\ heat}$	$\sum Total\ heat_{Monthly}$
Step 8	$Space\ heating_{Annual}$	$Annual_{Total\ heat} - Hot\ water_{Annual}$

Table 33. Adjustment 3 calculating space heating demand from annual meter readings.

4.5.5 Adjustment for boiler efficiency

The space heating demand calculation in PHPP does not take into account the efficiency of the gas boiler (Feist et al., 2015b). Therefore, an adjustment is needed if data is from gas meter readings (Site 13). A natural gas boiler efficiency of 89.5% (SEDBUK 2009) was assumed, the minimum requirement for Part L1A 2016 (DCLG, 2016). In reality, boiler efficiencies are likely to be less (NES, 2015), therefore this is a conservative approach which may lead to an overestimation of space heating demand.

4.5.6 Comparison of data collection methods

We determine the quality of results obtained from Adjustments 2 and 3, using the separately measured space heating and hot water use data from our 25 low-energy homes (two homes with zero measured space heating were excluded).

To apply Adjustment 2, monthly space heating and hot water data were combined to mimic Category B data. One outlier was removed as there was a fourfold difference between measured summer and winter hot water loads. The mean measured space heating demand was 11.68 $kWhm^2a^{-1}$, and the mean estimated space heating demand 10.64 $kWhm^2a^{-1}$. The mean difference between estimated and measured was found to be 0.03 $kWhm^2a^{-1}$ (<1% difference, s= 1.9 $kWhm^2a^{-1}$).

Similarly, to apply Adjustment 3, monthly space heating and hot water measurements were initially combined to create total monthly heat, and then further combined into two measurements, summer, and winter. The summer data contained the months of April, May, September, and October to ensure the method to estimated summer space heating was tested. This mimics Category C data. The mean measured space heating demand was 11.68 $kWhm^2a^{-1}$, and the mean estimated space heating demand 11.22 $kWhm^2a^{-1}$. The mean difference between estimated and measures using Adjustment 3 was -0.54 $kWhm^2a^{-1}$ (4% difference, s = 4.5 $kWhm^2a^{-1}$).

Results for both methods are summarised in Figure 30 and Figure 31 in Appendix 7. These relatively small differences provide confidence in the adjustments and were therefore applied to the Category B and C data.

4.6 Results

4.6.1 Space heating demand year 1

Annual space heating demand[14] for all the dwelling types is shown in Figure 24, with the mean target space heating demand computed from the prediction on the PHPP certificates, as well as the Passivhaus maximum of 15 $kWhm^2a^{-1}$.

[14] Unless otherwise stated, results use raw (i.e. not temperature normalised) data.

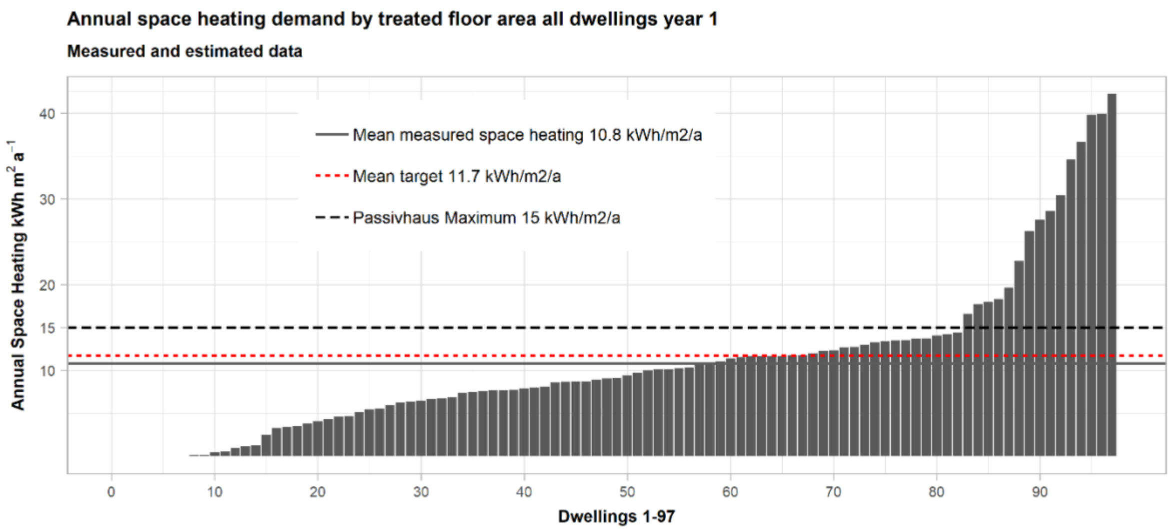

Figure 24. Measured space heating demand (kWhm2a-1) for 97 new build Passivhaus dwellings in the first year of operation, compared to the mean predicted demand on their Passivhaus certificates (red small dash) and the target maximum under the Passivhaus standard (15 kWhm2a-1, black wide dash).

We observe that the mean annual space heating demand for the 97 dwellings in our data set is 10.8 kWhm^{2}a^{-1} (s = 9.1 kWhm^{2}a^{-1}) compared to a mean target of 11.7 kWhm^{2}a^{-}1 (s = 3.2 kWhm^{2}a^{-1}). A paired t-test confirms these differences to be negligible (p = 0.43, Cohen's d = -0.1). As there are outliers at both ends, it is worth noting that the median demand is 9.2 kWhm^{2}a^{-1}, further below target demand. As the gap between mean target and mean measured space heating demand is -0.9 kWhm^{2}a^{-1} and on average the homes are performing as expected, we conclude there is no performance gap for the data set as a whole.

Figure 25 shows the difference between mean measured space heating demand (kWhm^{2}a-^{1}) for all available years (i.e. between 1–3 years) and the space heating demand prediction as shown on the Passivhaus Certificate for each dwelling. Of the 97 homes in our data set, 52 (54%) used less energy for space heating than predicted and 45 the same or more. The mean difference between mean measured annual space heating and the certified target is -0.11 kWhm^{2}a^{-1} (s = 9.5 kWhm^{2}a^{-1}).

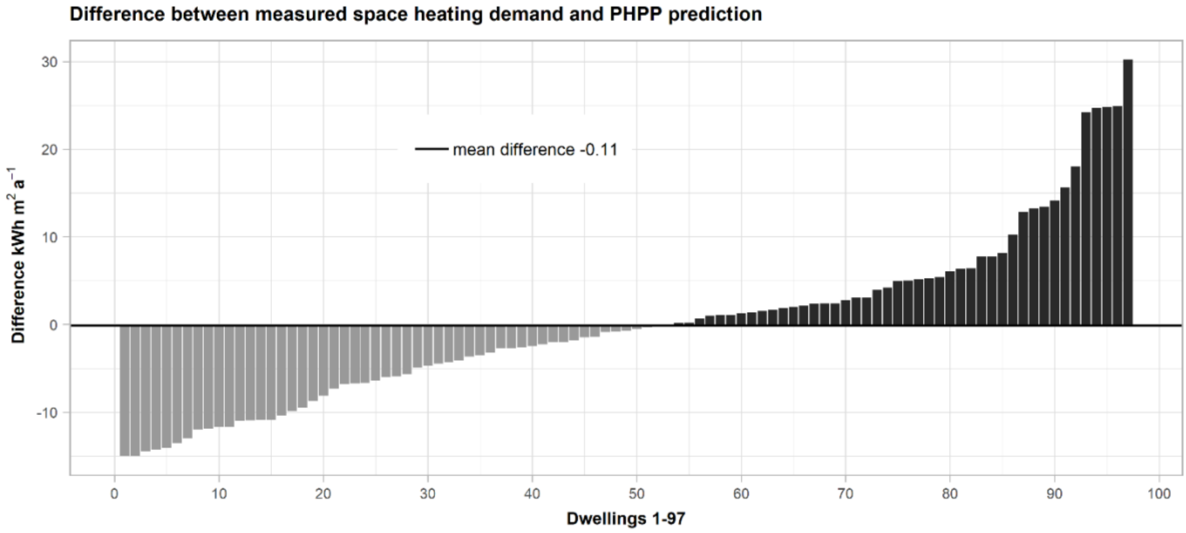

Figure 25. Difference between observed mean annual space heating demand with certified target for each dwelling for all years of operation. Negative numbers indicate dwellings used less heating than predicted.

4.6.2 Annual space heating demand by dwelling type

Figure 26 shows the mean annual space heating demand, separated into dwelling types (Houses and Flats).

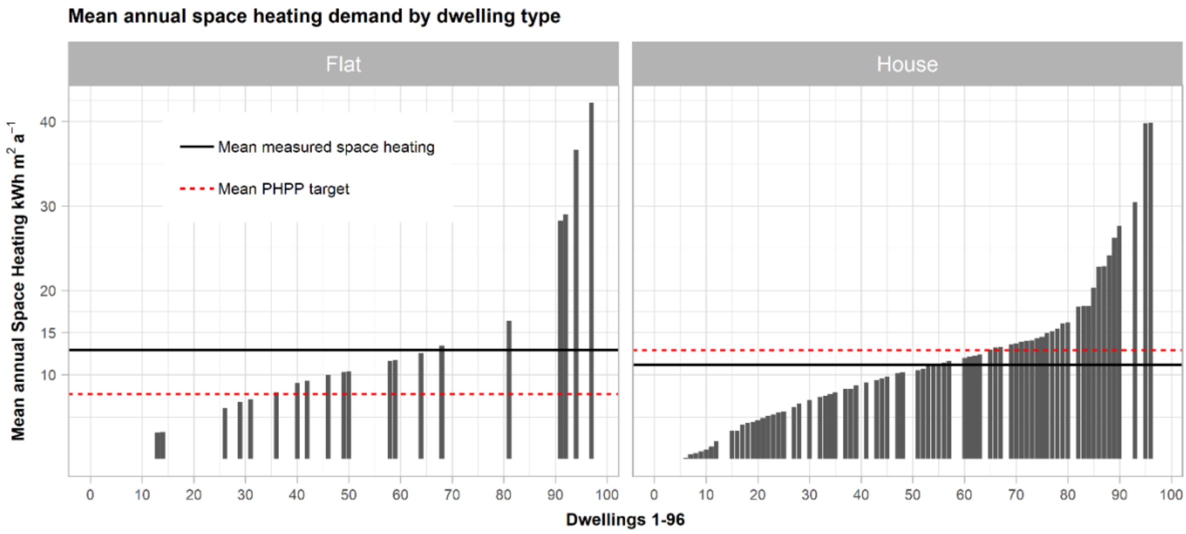

Figure 26. Mean annual space heating demand by dwelling type.

The mean space heating demand for flats was 12.9 kWhm^{2}a^{-1} compared to the mean target of 7.7 kWhm^{2}a^{-1}, but below the Passivhaus maximum of 15 kWhm^2 a^{-1}. The mean space heating demand for houses was 11.2 kWhm^2 a^{-1}, compared to a mean target of 12.9 kWhm^2 a^{-1}. Therefore, on average the houses were using less space heating demand than predicted and the flats more.

4.6.3 Annual space heating demand by data category

Figure 27 shows mean annual space heating demand separated into the three categories of data. The mean annual space heating demand for Categories A, B and C were 12.2 $kWhm^2 a^{-1,}$ 11.3 $kWhm^2 a^{-1}$ and 11.3 $kWhm^2a^{-1}$ respectively (standard deviations were 13. 5 $kWhm^2a$-^{1}, 5.7$kWhm^2a$-^{1} and 5.9 $kWhm^2a$-^{1}), compared to a mean PHPP prediction of 13.9 $kWhm^2 a^{-1}$, 12.2 $kWhm^2 a^{-1}$ and 8.0 $kWhm^2a^{-1,}$ respectively. Category A and B data were below the PHPP prediction. Category C data shows an increase in measured heating over PHPP prediction. This is likely due to the inclusion of 11 flats with a very low PHPP prediction of 4 $kWhm^2a$-^{1}, which resulted in a much lower mean target.

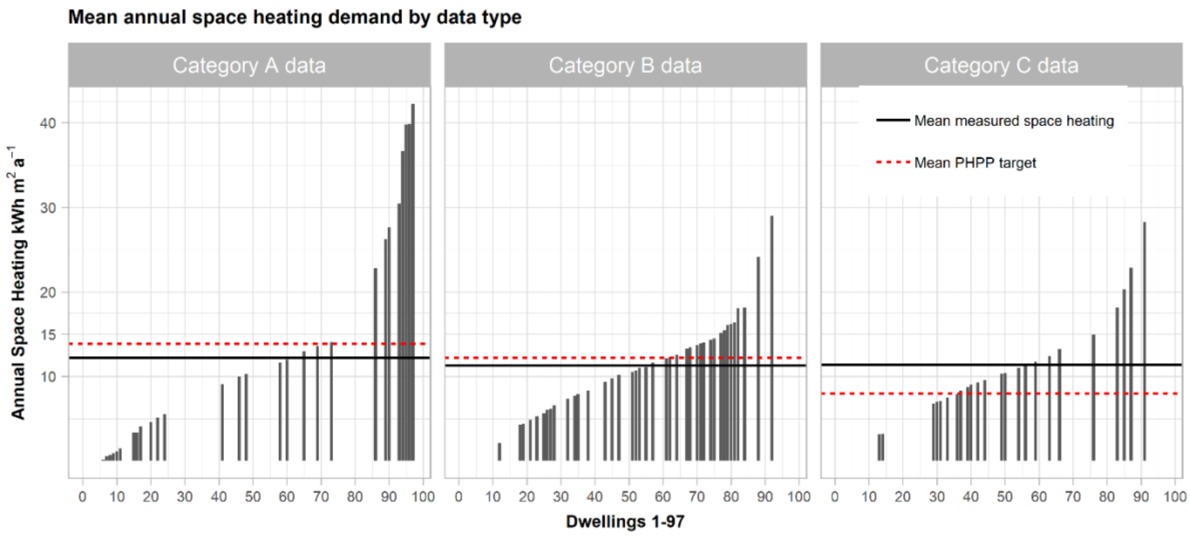

Figure 27. Mean annual space heating demand by treated floor area for each data category.

4.6.4 Normalisation of space heating demand

Internal temperatures were available for 56 homes, for which group the mean annual space heating demand was 11.9 $kWhm^2a^{-1}$, slightly above the mean target of 11.4 $kWhm^2a^{-1}$. Space heating demand for Year 1 was normalised using measured internal and external temperatures. This reduced the mean annual space heating demand of the 56 dwellings from 11.9 to 10.3 $kWhm^2a^{-1}$ (-1.6 $kWhm^2a^1$, Figure 28), further reducing average space heating demand below target demand. On average, for each 1°C temperature difference above or below 20°C, space heating demand increased or decreased by 1.9 $kWhm^2a^{-1}$ (16%).

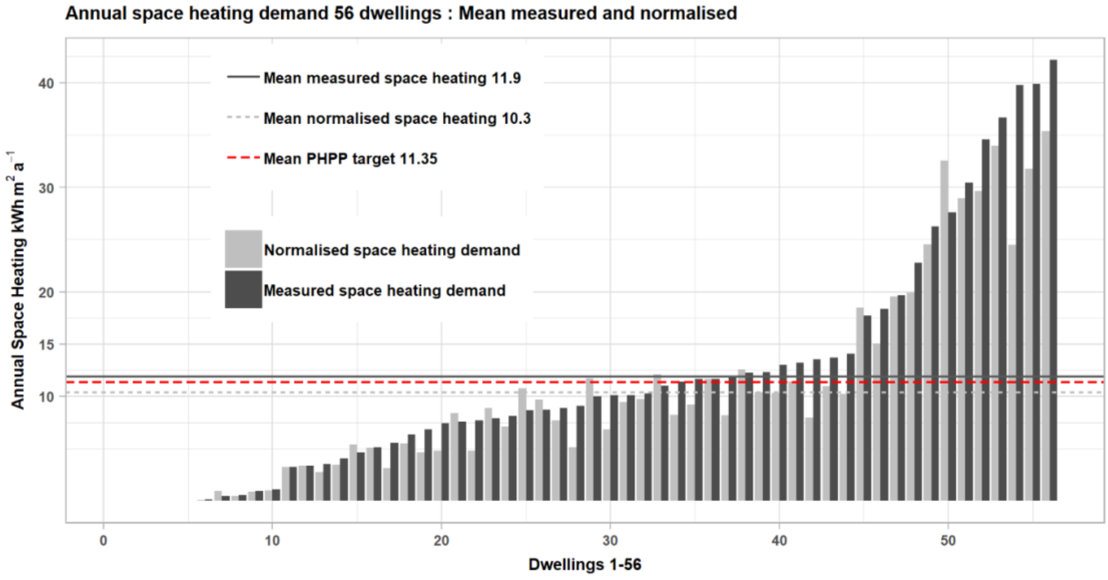

Figure 28. Temperature normalised annual space heating demand for 56 homes for which internal and external temperature data were available.

4.7 Discussion

The energy performance gap is a concern for both the construction industry and consumers. If homes consistently use more energy for space heating than predicted, this impacts on carbon emissions reporting at a governmental level, contributes to climate change and potentially places more people in fuel poverty. Therefore, having confidence that homes built to a certain standard meet that standard is vital for both improving energy efficiency in our homes and for managing carbon emissions reductions nationally. The three main reasons for the performance gap cited in the literature are (i) poor build quality on-site, (ii) occupant behaviour, and (iii) the limitation of building models.

Current consultation on the Future Homes Standard (FHS), due to be implemented in 2025, sets to at least halve the energy use from new buildings. The FHS includes measures to both increase the efficiency of new homes and reduce the performance gap. Our results show that UK homes built to the Passivhaus Standard do not show the same space heating performance gap as observed in the literature. Mean space heating demand (10.8 kWhm^{2}a^{-1}) is about 1 kWhm^{2}a^{-1} below the mean predicted space heating (11.7 kWhm^{2}a^{-1}), with no statistically significant difference. When comparing each dwelling with the prediction on the Passivhaus certificate, just over half of the dwellings used *less* energy for space heating demand than predicted (52 out of 97 homes). Houses used less space heating demand than predicted, on average, and the flats more – though this is likely biased by the relatively small sample of flats in our data set (20%), but all were well below target demand of 15 kWhm^{2}a^{-1}.

While occupant behaviour is a contributor to the performance gap, our results show that this can be limited though Passivhaus design. Ten homes had no space heating demand at all, 83 of the 97 (86%) homes used less than 15 $kWhm^2a^{-1}$. Only five homes (5%) used more than 30 $kWhm^2a^{-1}$, which is still below the predicted performance of a new build UK home. These results also show that Passivhaus homes are being consistently delivered in the UK, not just on individual projects, but also from large sites, with a mixture of tenures. The UK results are an improvement on the mean space heating from the EU CEPHEUS data (19.6 $kWhm^2 a^{-1}$), which suggests that knowledge, skills, and technologies have developed within the 15 years between the two data sets. While the UK homes had, on average, less annual space heating demand, the standard deviations are comparable to those observed in CEPHEUS. Such similarities over these large data sets are suggestive of the typical effect that uncertainties such as occupant behaviour may have on demand.

Normalisation can reduce the limitation of building models, the third element of the performance gap. The results showed that internal and external temperature normalisation reduced the mean space heating demand by 1.6 $kWhm^2a^{-1}$, or 13%. Within the data set, for each 1°C difference in internal temperature from the modelling assumption, there was a mean space heating difference of 1.9 $kWhm^2a^{-1}$. This was in line with the findings of the Passive House Institute (Peper, 2017) and shows the need to include normalisation as part of any monitoring programme, as small temperature differences can result in noticeable changes to space heating demand.

As there is a lack of post-occupancy data from buildings, our data set included three categories of collection: disaggregated heat metering (A), monthly total heat (B), and bi-annual meter readings (C). Reassuringly little difference was observed between the mean measured space heating demand in each (Category A 12.2 $kWhm^2a^{-1}$, Category B 11.3 $kWhm^2a^{-1}$ and Category C 11.3 $kWhm^2a^{-1}$). Category A and Category B data were less than predicted, with Category C data slightly higher, likely due to the large number of flats with low predicted demand. Category A data had the greatest standard deviation, 13.5 $kWhm^2a^{-1}$, compared to 5.7 $kWhm^2a^{-1}$ and 5.9 $kWhm^2a^{-1}$ for the other categories. This is not unexpected, as Category 1 contained the largest number of sites (11 out of 13) and therefore a bigger variation in dwelling types and construction methods.

The inclusion of these diverse categories of data implied the need for adjustments to extract the space heating demand component where this was not directly measured (Categories B and C). The two adjustment procedures shown here were tested against data where space heating demand was separated from total heat. Of the two, Adjustment 3 (applied to Category C) slightly overestimated space heating demand which is within the ethos of taking a cautious approach. Both adjustments rely on assumptions about hot water use over the year which can vary considerably and can therefore significantly impact space heating demand estimates. Adjustment 2 (applied to Category B) is more accurate as data can be taken from monthly readings when it is reasonable to assume there is no space heating demand. Adjustment 3 relied on assumptions about the ratio of monthly total heat to annual total heat. This can vary considerably (see Figure 21) and is dependent on household composition and hot water use patterns. The database to calculate the total heat ratios was small (25 homes) and a larger database would yield more typical usage patterns. However, both adjustments performed well, though Adjustment 2 was better due to the higher temporal resolution, as above. Therefore, these adjustments can be powerful tools in estimating space heating demand in the presence of limited data. Adjustment 2, especially, implies that the collection of non-forensic building performance data (i.e. at the dwelling level) at-scale could be achieved at lower cost through monthly total heat data collection rather than the extra investment into disaggregated metering.

To improve energy efficiency and reduce carbon emissions, the FHS is considering combining improved building fabric and the integration of low carbon heat. This would be governed by limitations on a main metric of primary energy, a secondary metric of carbon emissions and introduce a third affordability index to ensure that new homes can be heated at a reasonable cost. To reduce the performance gap, future compliance with Part L could include improving quality control on-site, focusing on installation of insulation, detailing around windows, reducing thermal bridging at junctions, improving airtightness, and introducing site checks, including providing photographic evidence. All of these are already part of the Passivhaus certification process, to maintain quality control between design and construction.

The other significant concern with highly insulated homes is the perceived risk of greater overheating compared to less insulated homes. However, recent work has provided strong evidence against this, both through a comprehensive global-scale modelling study (Fosas et al., 2018), as well as large-scale observational data of Passivhaus homes in the UK (Mitchell and Natarajan, 2019) which can be favourably compared to data from typical homes (Hughes and Natarajan, 2019, Vellei et al., 2017). These results strongly suggest that Passivhaus buildings overheat either at the same or lower rate than comparable typical, less insulated, buildings.

4.8 Conclusion

Overall, our results provide clear evidence that compliance with the Passivhaus standard delivers low-energy homes, with no performance gap, which are affordable to heat and without the need for complex metrics. When taken together, with the lack of evidence for increased overheating risk, the Passivhaus approach emerges as a “proven” candidate for off-the-shelf adoption within the Future Homes Standard as a method whose as-built performance can be clearly demonstrated at-scale. Since the Future Homes Standard is expected to be in place five years from the time of writing, our results are not only timely, but also provide, for the first time, the comprehensive evidentiary basis that is needed to transform the future design and construction of homes in the UK.

4.8.1 Acknowledgements

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4.10 Appendices

4.10.1 Appendix 1 Space heating and temperature data

Space heating and temperature data came from a variety of sources which are summarised in Table 34 below. On some smaller sites all the dwellings were measured, and on larger developments only a selection of the dwellings.

			Sources of space heating data		Source of temperature data		
Site	**Number of dwellings with data**	**Total dwellings on-site**	**Source of space heating data**	**Heating system**	**Internal**	**External**	**Length of monitoring period**
Category A data							
Site 1	3	3	Space heating separately sub heat metered on-site; raw data provided by consultant	Gas boiler for heating and hot water	Hourly temperature sensor in living room	Hourly external sensor on-site	2 years
Site 2	12	20	Space heating separately sub metered on-site, raw data provided by consultants	Gas boiler for heating and hot water	Hourly temperature sensor in living room	Daily data from local weather station	1 year
Site 3	1	1	Underfloor space heating separately sub-metered, annual reading provided by owner	Gas boiler for heating and hot water	Hourly temperature sensor in living room	Daily data from local weather station	2 years
Site 4	1	1	Sub metered data from Innovate UK	Gas boiler for heating and hot water. Electrical post heater in MVHR unit separately metered	Hourly temperature sensor in living room	Hourly external sensor on-site	1 year
Site 5	3	18	Innovate UK data and report card, space heating separately sub metered	Electrical post heater in MVHR unit and solar hot water	5-minute temperature sensor in living room	15-minute external temperature sensor	1 year

Site 6	2	2	Sub metered data from Innovate UK	Gas boiler for heating and hot water Solar hot water. Electrical post heater in MVHR unit separately metered.	5-minute temperature sensor in living room	5-minute external temperature sensor	2 years
Site 7	1	1	Sub metered data from MVHR electrical element, wood use from Innovate UK report card. Data for towel rail not available.	Electrical post heater in MVHR unit, wood stove and electrically heated towel rail	5-minute temperature sensor in living room	5-minute external temperature sensor	2 years
Site 8	2	3	Innovate UK report card, space heating separately sub-metered	Electrical post heater in MVHR unit, solar hot water in one unit	5-minute temperature sensor in living room	5-minute external temperature sensor	1 year
Site 9	2	5	Innovate UK report card. Combination of sub metering and manual meter readings with some assumptions.	LPG gas heating and hot water. Electrical post heater in MVHR unit, solar hot water.	5-minute temperature sensor in living room	5-minute external temperature sensor	1 year
Site 10	4	8	Sub metered data from Innovate UK	Wood stove and solar hot water to thermal store for direct heating and hot water and post heater in MVHR unit	5-minute temperature sensor in living room	5-minute external temperature sensor	1 year
Site 11	1	28	Sub metered data from Innovate UK	Electrical post heating in MVHR unit	10-minute temperature sensor in living room	10-minute external temperature sensor	1 year
Total	32						
Category B data							
Site 12	41	42	Total heat (space heating and hot water) metered to each dwelling from centralised boiler. Monthly readings from heat exchanger.	See adjustment on separating heating from combined data	n/a	n/a	3 years
Total	41						
Category C data							
Site 13	24	38	Total heat (space heating and hot water) from individual	See adjustment on separating heating from combined data	Hourly temperature sensor in living room	Daily data from local weather station	2 years

			gas boilers. Biannual gas meter readings.				
Total	24						
Total all units	**97**						

Table 34. Source of space heating data for the Passivhaus database.

Dwelling Types

Within the monitored units on the 13 sites, there were the following dwelling types.

Dwelling Type	House	Flats	Total
Houses	75	19	97

Table 35. Number and type of dwellings.

4.10.2 Appendix 2 Meter readings dates Site 12 (Category 3 data)

Year 1

Meter reading dates				**Meter reading dates**			
Dwelling	Reading date 1	Reading date 2	Reading date 3	Dwelling	Reading date 1	Reading date 2	Reading date 3
1	31/08/2015	17/03/2016	13/09/2016	13	31/08/2015	17/03/2016	13/09/2016
2	31/08/2015	17/03/2016	07/10/2016	14	31/08/2015	08/01/2016	13/09/2016
3	31/08/2015	17/03/2016	13/09/2016	16	31/08/2015	17/03/2016	12/09/2018
4	31/08/2015	17/03/2016	13/09/2016	16	31/08/2015	08/01/2016	12/09/2016
5	31/08/2015	17/03/2016	13/09/2016	17	31/08/2015	17/03/2016	12/09/2016
6	31/08/2015	17/03/2016	13/09/2016	18	31/08/2015	17/03/2016	12/09/2016
7	31/08/2015	17/03/2016	06/10/2016	19	31/08/2015	17/03/2016	12/09/2016
8	31/08/2015	17/03/2016	10/10/2016	20	31/08/2015	17/03/2016	12/09/2016
9	31/08/2015	25/05/2016	06/10/2016	21	31/08/2015	17/03/2016	12/09/2016
10	31/08/2015	07/04/2016	10/10/2016	22	31/08/2015	08/01/2016	12/09/2016
11	31/08/2015	03/06/2016	06/10/2016	23	31/08/2015	17/03/2016	12/09/2016
12	31/08/2015	17/03/2016	07/10/2016	23	31/08/2015	17/03/2016	12/09/2016

Year 2

Meter reading dates				**Meter reading dates**			
Dwelling	Reading date 1	Reading date 2	Reading date 3	Dwelling	Reading date 1	Reading date 2	Reading date 3
1	13/09/2016	20/03/2017	29/09/2017	13	12/09/2016	20/03/2017	11/09/2017
2	13/09/2016	20/03/2017	11/09/2017	14	12/09/2016	20/03/2017	11/09/2017
3	13/09/2016	20/03/2017	11/09/2017	16	12/09/2016	20/03/2017	11/09/2017
4	13/09/2016	20/03/2017	11/09/2017	16	12/09/2016	20/03/2017	11/09/2017

5	06/10/2016	20/03/2017	26/09/2017	17	12/09/2016	20/03/2017	27/09/2017
6	10/10/2016	20/03/2017	11/09/2017	18	12/09/2016	20/03/2017	11/09/2017
7	06/10/2016	20/03/2017	11/09/2017	19	12/09/2016	20/03/2017	11/09/2017
8	10/10/2016	20/03/2017	11/09/2017	20	12/09/2016	20/03/2017	11/09/2017
9	06/10/2016	20/03/2017	27/09/2017	21	12/09/2016	20/03/2017	11/09/2017
10	13/09/2016	20/03/2017	11/09/2017	22	12/09/2016	20/03/2017	11/09/2017
11	13/09/2016	20/03/2017	27/09/2017	23	12/09/2016	20/03/2017	11/09/2017
12	12/09/2016	20/03/2017	11/09/2017	23	12/09/2016	20/03/2017	11/09/2017

Table 36. Summary of meter reading dates Site 12.

4.10.3 Appendix 3 Normalisation method

Steady-state building simulation models such as Passive House Planning Package (PHPP) assume monthly fixed internal temperatures and degree days from regional climate data to estimate space heating demand (Mead and Brylewski, 2010, Feist et al., 2015b). Site and time-specific weather is likely to be different from those assumed from long-term records. These differences in external temperatures could result in higher or lower heating demand than predicted during modelling (CIBSE, 2006) and for low-energy homes such as Passivhaus this difference could be as much as 5 kWhm^{2}a^{-1} (Peper, 2017).

In addition, many occupants heat their homes to higher than assumed internal temperatures or for longer, for comfort reasons (Exner and Mahlknecht, 2012, Vadodaria, 2014), which will create a disparity between assumed and real internal temperature differences. For example, post-occupancy data from European Passivhaus studies show typical internal temperatures to range between 21°C and 24°C (Schnieders, 2003a, Exner and Mahlknecht, 2012). Internal temperatures are known to have a significant impact on space heating demand and typically it is estimated that a 1°C increase in internal temperature translates to a 10% increase in space heating demand (Palmer et al., 2012). In Passivhaus buildings, this increase is greater and for each 1°C temperature above 20°C, space heating consumption can rise by 2kWh m^{2}a^{-1}(Peper, 2017). As space heating demand is already low, this translates to a 12–15% increase per 1°C (Peper, 2017). Therefore a Passivhaus home with a 22°C winter internal temperature may have a space heating demand between 4 and 5 kWh m^{2}a^{-1} above planned consumption (Peper, 2017). Hence, when comparing “predicted” and “observed” demand, it is important to normalise for both the above effects, to ensure a like for like comparison.

Hence, normalising for internal and external temperatures will ensure that any gaps between predicted and measured space heating demand, which can be accounted for by temperature differences between measured conditions and modelling assumptions, are identified and accounted for. The CEPHEUS project described a normalisation method to correct for actual internal temperatures, taking into account measured external temperatures and solar radiation (Schnieders, 2003a, Schnieders, 2015), seen in Table 37 .

Step	Variable to compute	Explanation
Step 1	$Q\ Heating_{measured}$	Measured annual space heating demand (kWh)
Step 2	$Q\ Heating_{20}$	Modelled annual space heating demand (kWh) summed from monthly values in PHPP using measured monthly external temperatures and solar radiation manually inputted into the 'climate' sheet and the standard internal temperature of 20˚C in the 'verification' sheet.
Step 3	$Q\ Heating\ _{real}$	Same as $Q\ Heating_{20}$ but with measured monthly internal temperatures, manually inputted into the 'verification' sheet.
Step 4	Calculate normalisation factor (f_{ti})	$fti = \frac{Q\ Heating_{20}}{Q\ Heating_{real}}$
Step 5	Apply normalisation factor to measured space heating	$Q\ Heating_{norm} = QHeating_{measured} * \text{ fti}$

Table 37. Summary of normalisation method from CEPHEUS (2003). The 'climate' and 'verification' sheets refer to those sheets in PHPP and contain the external weather data and internal temperature data, respectively.

This method has been modified to consider internal and external temperature differences at step 2 and the step 3 calculation of Q Heating $_{20}$. Solar radiation and internal heat gains were not included, as these variables were found to have minimal impact on the calculation of the correction factors (Mitchell and Natarajan, 2018). The amended method is described in Table 38.

Amended Step 2	$Q\ Heating_{20}$	Modelled annual space heating demand (kWh) summed from monthly values in PHPP using site-specific *regional climate data* for monthly external temperatures and solar radiation from the 'climate' sheet and the standard internal temperature of 20°C in the 'verification' sheet.
Amended Step 3	$Q\ Heating\ _{real}$	Same as $Q\ heating_{20}$ but with *measured monthly internal temperatures,* manually inputted into the 'verification' sheet and *measured monthly external temperatures* manually inputted into the 'climate sheet'.

Table 38. Amended method for normalisation for internal and external temperatures.

The CEPHEUS methodology assumes there is access to the original PHPP for each site, which may not always be possible. We have previously shown that normalising using this method is possible using any PHPP assessment, provided measured internal temperatures do not fall well below 20°C (Mitchell and Natarajan, 2018). As there was no access to the

PHPP assessment for all the sites, a single domestic PHPP from a different site was used to undertake normalisation.

4.10.4 Appendix 5

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Proportion	0.147	0.122	0.098	0.078	0.061	0.050	0.044	0.044	0.053	0.070	0.097	0.135	1

Table 39. Percentage of monthly total heat to annual total heat.

4.10.5 Appendix 6 Treated Floor Area (TFA)

Figure 29 shows the Treated Floor Area (TFA) for each dwelling. Most dwellings had a TFA of less than 100m², except for three houses, two of which were over 300m². Houses are shown in light grey, flats in black. All flats were between 39m² and 67m².

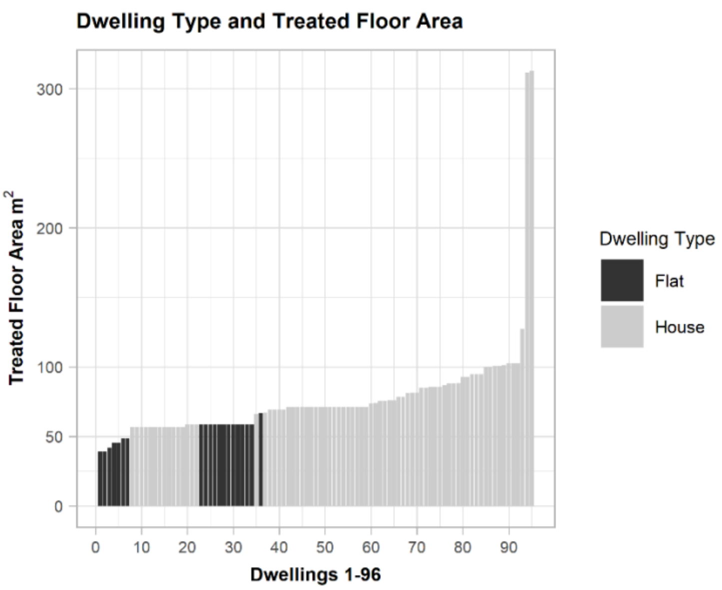

Figure 29. Dwelling type and Treated Floor Area (TFA).

4.10.6 Appendix 7 Comparison of data collection methods: Adjustments 2 and 3

Figure 30 shows a comparison of the measured annual space heating demand by TFA (light grey columns) to estimated annual space heating by TFA (dark grey columns) using Adjustment 2.

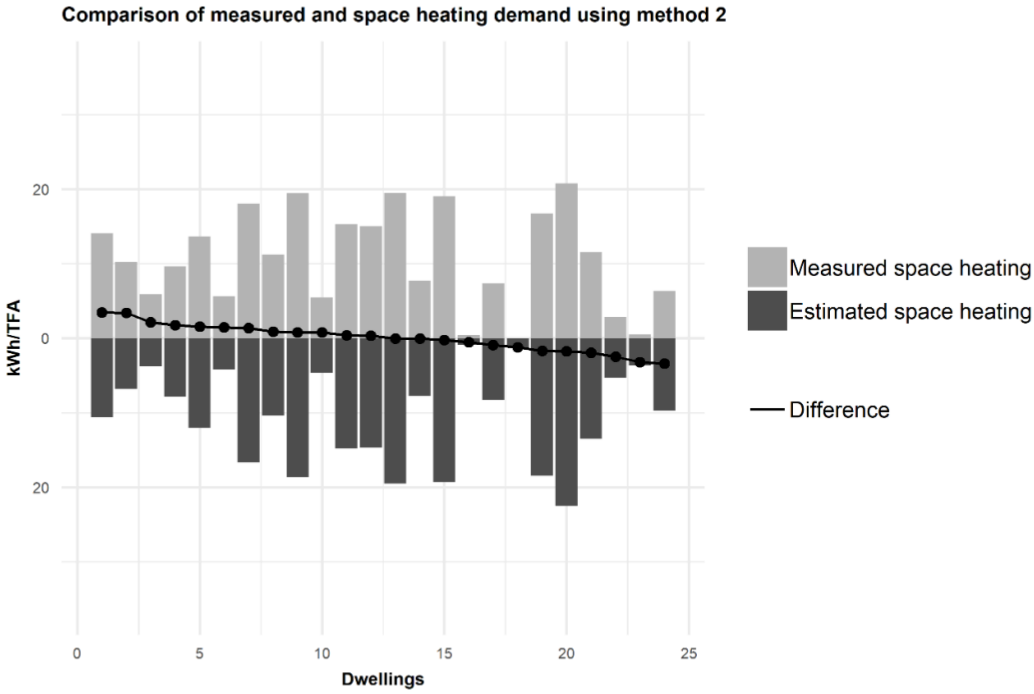

Figure 30. Comparison of annual measured and estimated space heating demand using Adjustment 2 on measured data from low-energy dwellings

Figure 31 shows a comparison of the measured annual space heating demand by TFA (light grey columns) to estimated annual space heating by TFA (dark grey columns) using Adjustment 3.

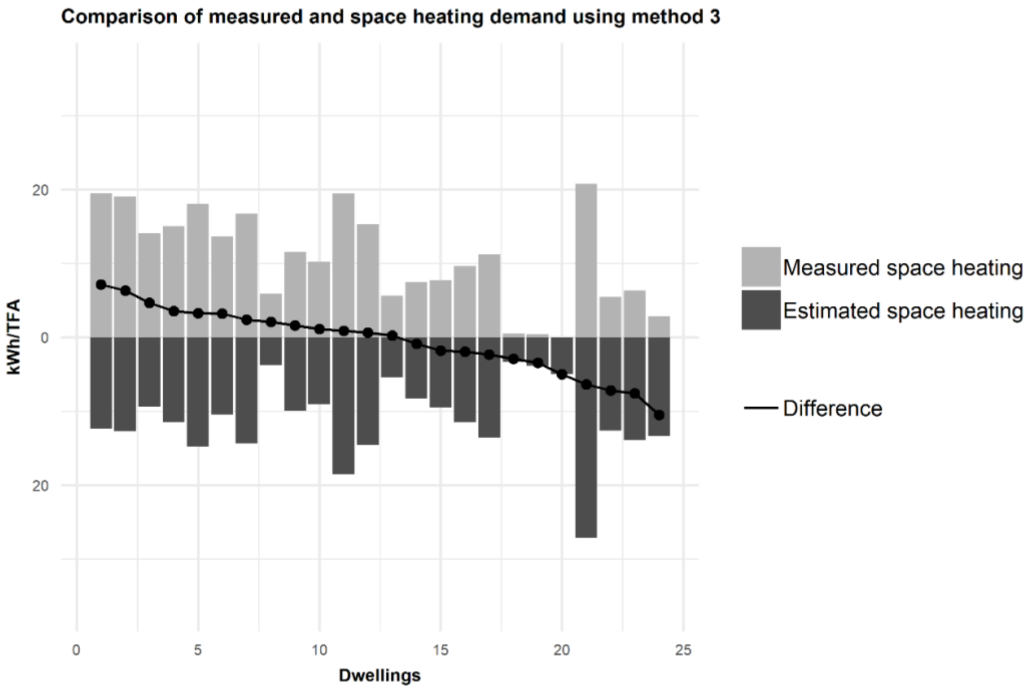

Figure 31. Comparison of annual measured and estimated space heating demand using Adjustment 3 on data from low-energy dwellings.

4.11 Postscript

This chapter demonstrates there is a negative EPG for space heating in UK dwellings build to the Passivhaus standard, i.e. mean measured space heating demand is *less* than the mean predicted in PHPP. This research supports the growing body of evidence that the EPG is less prevalent in homes built to the Passivhaus standard compared to other low-energy codes (Gupta et al., 2019), and demonstrates it at a large scale.

Whilst some homes used more energy for space heating than modelled, more dwellings used less energy than PHPP predicted. Even those homes with greater than estimated space heating can still be considered low-energy homes which protect the occupant from fuel poverty. For example, if a typical UK dwelling, with a floor area of $100m^2$, uses 10 $kWhm^2a^{-1}$ more for space heating (1000 kWh per year), this is an additional cost of £40 per annum base on a gas heating system. Even the dwelling with the greatest annual heating (42 $kWhm^2a^{-1}$) is less than the predicted heating demand of a dwelling constructed to current UK building regulations ($50m^2a^{-1}$), which in-use could be much greater once the EPG was factored in. This addresses the first part of Research Question 3 and demonstrates that certified homes built to the Passivhaus standard are meeting that standard in-use for space heating demand.

By including 97 dwellings in the dataset there are sufficient numbers to reduce the effect size to less than 0.3 (p 0.05). Therefore, we can conclude there are enough dwellings to have confidence in the findings and to evaluate the delivered performance of Passivhaus in the UK with confidence. This is the largest reported sample size of Passivhaus homes in the UK and the first comprehensive review of the available post-occupancy data on space heating and hence addresses the second part of Research Question 2.

Internal temperature normalisation reduced mean space heating demand by 15%. This has implications for EPG calculations and demonstrates that normalisation should be undertaken to ensure this element of user behaviour can be excluded. Each 1°C temperature increase above 20°C typically increased space heating demand by 1.9 $kWhm^2a^{-1}$ or 16%. This is in line with the finding of the Passive House Institute which assumes a 2 $kWhm^2a^{-1}$ increase per K above 20°C (Peper, 2017).

The third part of Research Question 3 covers data collection methods other than heat metering. All heat meters will have some margin of error, which on average is between 3%–9% and can be as great as 60% (Butler and Abela, 2016). Two alternative adjustments tested against known data. Adjustment 2, (based on monthly total heat meter readings) had an SD of 1.8kWhm^{2}a^{-1} and a margin of error of 15%. Whilst not as accurate as heat metering, for a low cost and simple approach to estimating space heating demand, this margin of error may be acceptable. As complexity and costs are barriers to data collection, this simplified method could allow much greater data collection and provide the feedback loops needed to inform the construction industry. In the context with other findings in this chapter, this margin of error is similar to a 1°C internal temperature increase, i.e. the difference between normalised and non-normalised space heating data.

Adjustment 3, which was based on bi-annual meter readings but could be applied to an annual meter reading, represents minimum data collection. As a result of this limitation, the margin of error increased to 21%, which may be considered too great to give meaningful data. However, if only a basic understanding of building performance is needed then this very low-cost approach would give some insight into energy performance.

Differences between predicted and measured space heating demand are one example of a performance gap between design expectations and the reality in-use. As Passivhaus is not only an energy standard but a comfort standard too, higher than expected internal temperatures will also be a performance gap issue, if these higher temperatures cause overheating and discomfort.

Chapter 5 Summary and conclusion of findings

This thesis has answered three research questions which relate to the performance gap in new homes. To do this a new POE dataset from UK-certified PH dwellings has been created. This is the first time that data from this number of dwellings (97), from different sites (13), has been collected and presented. The purpose was to look for evidence of the EPG, specifically in space heating demand and overheating risk. Typically, research in this area has been small-scale, which limits the inferences that can be drawn from the results. By collating data from this number of dwellings, a meta-analysis can be undertaken, and conclusions made which can be applied to the wider research and government policy on the delivery of low-energy homes.

Evidence of the EPG is found when in-use data is different from building modelling predictions. As discussed in Chapter 1, the reasons for this are varied and complex. Therefore, if known discrepancies can be accounted for, these should be identified and excluded to ensure the best fit between the building models and in-use environment. The published paper presented in Chapter 2 developed a novel way of employing widely used building models to normalise for internal temperature and external weather conditions. This addressed Research Question 1. *Can a simplified method for temperature and weather normalisation be developed, which can be applied to measured space heating data from dwellings post-occupancy, when there is no access to the original building model, or information on the building geometry and specification*?

When reporting on data collected by a third party, it is very often the case that there is no access to the building models used to predict space heating demand. As outlined in Chapter 1 and Chapter 2, higher than predicted internal temperatures correlate to higher than predicted space heat demand. For PH buildings this can be 2 $kWhm^2a^{-1}$ for each K temperature difference above 20°C (Peper, 2017). With a maximum space heating demand of 15 $kWhm^2a^{-1}$, a 1°C increase in internal temperature would show a EPG of 13% and a 2°C temperature, an increase of 27%. Therefore, internal temperature normalisation is critical in low-energy homes such as PH, to ensure this variable is accounted for when looking for evidence of the EPG.

Our method calculated a normalisation factor (f_{ti}), which corrected for three variables: internal temperature, solar and internal gains. By interchanging these into four cases, creating 400 model variants, tested over 20 dwelling types, it was possible to isolate internal temperature as the variable that most influenced the calculation of f_{ti}. When internal temperature was >20°C, the calculation of f_{ti} was remarkably consistent. This method was then applied to the commonly used domestic building models PHPP and SAP (2012). The results showed that regardless of building geometry and function, f_{ti} remained consistent and building models could be interchanged. When f_{ti} was applied to space heating demand, the maximum standard error was 0.4 $kWhm^2a^-1$, or a 4% error rate. This has two useful applications:

1. If there is no access to the original building model, an alternative model can be used with confidence. This will allow temperature normalisation, when in the past it could not.
2. As internal temperature is identified as having the greatest impact, only this variable needs to be collected on-site for accurate normalisation. This impacts on time, costs, and complexity.

This method was then applied to the data collected in Chapter 4. This allowed more dwellings to be normalised, and therefore a more accurate evaluation of the EPG made.

Much of the research into the performance gap focuses on energy use. Overheating is also emerging as a performance gap issue, with a concern that highly insulated homes are at a higher risk of overheating. Chapter 3 presents the paper *Overheating risk in Passivhaus dwellings*. This paper directly addresses Research Question 2. *As internal comfort is part of the Passivhaus certification criteria, is there a performance gap between summer internal temperatures and the maximum allowable overheating as defined by the Passivhaus certification method? How does modelling of overheating risk in PHPP compare with other methods such as CIBSE TM59 for domestic dwellings? Would the results in one standard (PHPP) predict the results in another standard (TM59) and what are the key lessons to learn?*

This paper examines internal temperature data from 82 UK Passivhaus dwellings, and compared internal temperatures outside of the heating season to the PH limits and CIBSE TM59. These standards have different methodologies. PH uses a fixed maximum for internal temperature and is applied to the whole house. CIBSE TM59 uses adaptive comfort with varying maximum internal temperatures, with a separate criterion for bedrooms (TM59-1B). Our results found 83% of dwellings complied with the maximum limits of the PH standard, however there was concern that the whole house method masked overheating in bedrooms which, when separately measured, has a lower compliance rate (65%). There is good practice PH guidance for overheating risk, which reduces the percentage of hours of high internal temperatures allowable from 10% to 5%. When this metric was applied (PH-5%)

whole house compliance reduced to 63% and to 55% for bedrooms. When comparing to CIBSE TM59, the adaptive comfort method allowed more rooms to comply compared to PH. However, when the more exacting bedroom standard (TM59-1B) was applied, less than half of these rooms met the criteria (45%). When comparing the two approaches, there was a strong match between TM59-1B and PH-5%. It was concluded that using this more stringent approach (PH-5%) at design stage would give greater confidence in reducing overheating in-use, especially in bedrooms.

The results from Chapter 3 have two useful applications

1. Most homes were not overheating as defined by the PH standard, but bedrooms are at risk. This was also the case with CIBSE TM59. Therefore, these are the rooms that need particular attention. By applying PH-5% to the whole house at design stage, bedrooms are better protected.
2. The overheating assessment methods were interchangeable. PH-5% and TM59-1B matched well, with one standard predicting compliance with the other. Therefore, either could be used to predict overheating risk. Compliance with TM59-1B meant that there was compliance with all elements of the TM59 standard, therefore only this element needs to be met.

When comparing our results to the existing research, we can see that overheating risk is not just confined to PH homes in the UK and similar results are found in new non-PH homes (Jones et al., 2016, Gupta and Kapsali, 2015). As shown in our results, bedrooms were found to be particularly vulnerable to overheating (Gupta et al., 2019). In addition, overheating risk is not only confined to new UK homes. In the south west, 27% of bedrooms in 46 existing homes were found to be overheating (Vellei et al., 2016). In London, in a sample of 122 homes constructed between pre-1900 and 2006, 37% of living rooms and 49% of bedrooms showed overheating, using TM59 (Pathan et al., 2017). This increased to 94% of bedrooms in the atypically warm UK summer of 2018 (Hughes and Natarajan, 2019), thus showing that overheating is set to increase as temperatures rise. This is confirmed by building modelling, especially the vulnerability of bedrooms. When TM59-1B was tested against future climate data (2020–2080 climate files), severe overheating was predicted in a large scale retrofit to nZEB standards (Salem et al., 2019).

The existence of overheating in both new and existing homes suggests better models are needed to predict risk, especially in bedrooms. For UK homes, limiting the effects of heat gains in summer is included in Part L1A, and focuses on managing solar, gains, internal gains and ventilation (DCLG, 2013), however as discussed in Chapter 1, SAP is not considered suitable for either modelling overheating strategies (AECOM, 2012a) or the interaction of complex factors such as thermal mass or night time ventilation (NHBC, 2012c), the latter of which is a critical part of the overheating reduction strategy in low-energy dwellings. PHPP also relies on fixed internal temperatures applied to a single zone. This raises the question of whether steady state models can begin to predict the dynamic and complex interrelationship of temperature, airflow, shading, and user behaviour (Lomas and Porritt, 2017). Thus, we have suggested in Chapter 3 to move away from the whole house method for PH and allow modelling of individual rooms.

Even when using dynamic modelling, when comparing measured data it is difficult to get accurate predictions, particularly in bedrooms and when outdoor temperatures are high (Lomas and Porritt, 2017). As found in our and other’s research, bedrooms are most vulnerable to overheating and therefore the most in need of accurate modelling predictions.

The existence of overheating in PH homes is not evidence that there is a fundamental flaw in PH design which will result in overheating, but that overheating needs to be considered in all new and existing homes. When further investigation is undertaken, either by building modelling (Fosas et al., 2018) or detailed analysis of the causes of overheating risk in highly insulated and airtight homes, it is often linked to user behaviour (lack of window opening or employment of devices, disabling MVHR, higher than predicted internal gains) (Ridley et al., 2014, Sameni et al., 2015, Innovate UK, 2014c). This suggests that occupants may need to become more ‘active’ in managing overheating risk, through increasing summer ventilation rates and employing shading devices (Zhao and Carter, 2020). Indeed, a comparison of similar buildings in similar locations concluded that occupant behaviour was the variable that most influenced overheating, which can be based on perceptions. Some occupants reported overheating when internal temperatures were low, and others did not report when the temperature exceeded the limits of PH (Morgan et al., 2017).

Chapter 4 gathered and analysed POE data from 97 certified PH homes in the UK. This is presented in the published paper *UK Passivhaus and the energy performance gap*. This paper addresses Research Question 3. *How do Passivhaus dwellings in the UK perform once occupied, compared to the space heating prediction from design models (PHPP)? Can sufficient data from enough dwellings be collected to consider the UK application of the energy standard as a whole rather than on a case by case basis. Are there methods which can be applied to maximise data collection, when there is limited data available and how accurate would this data be compared to typical collection methods such as heat metering?*

The results demonstrate that while some homes used more energy than predicted and other less, there is no evidence of the EPG in the data set as a whole. Mean measured space heating was 10.8 kWhm^{2}a^{-1}, compared to the mean target of 11.7 kWhm^{2}a^{-1}. When normalised for internal temperature, mean measured space heating reduced further to 10.3 kWhm^{2}a^{-1}. As expected, there are variations within the data set. When comparing individual predicted and non-normalised measured space heating, SD is 9.7 kWhm^{2}a^{-1}. However, the mean difference between these two metrics is -0.11 kWhm^{2}a^{-1} and over half the homes were using less space heating than predicted in PHPP. Therefore, we can have confidence from this data set that the PH standard is being robustly delivered in the UK.

Data from eight of the sites came from the Building Performance Evaluation program (BPE) and has been used in further research. Fourteen PH were compared with 57 low-energy non-PH homes (meeting EcoHomes or Code for Sustainable Homes standards). The results showed that, while there was a gap between mean modelled PH (8.8 kWhm^{2}a^{-1}) vs mean measured PH (23 kWh m^{2}a^{-1}), this gap is much lower than non-PH homes, with mean modelled non-PH (30.5 kWhm^{2}a^{-1}) vs mean measured non-PH (58.3 kWh m^{2}a^{-1}), and PH homes showing half the EPG. Designing to PH standards also reduced the impact of outliers. Maximum measured space heating within the PH cohort was 50.2 kWh, compared to a non-PH maximum of 175 kWh m^{2}a^{-1} (Gupta et al., 2019). Whilst there is evidence of EPG within these PH dwellings, the PH dwelling with the maximum space heating demand was still over 70% lower than the non-PH home.

In our research, we found no EPG between mean measured and mean predicted space heating. When normalisation was applied the negative gap between mean predicted and measured *increased*. In addition, more than half the data set (52% of 97 homes) use less space heating demand than predicted. As the paired t-test confirms these differences to be negligible ($p = 0.43$, Cohen's $d = -0.1$), we can have confidence in both the results and the delivery of the PH standard.

There are also variations within our data set, however again PH limit these variations. Using non-normalised data, our data set showed a maximum space heating demand of 42.2 kWhm^{2}a^{-1} or +30.5 kWhm^{2}a^{-1} above mean target, which, when compared to the non-PH maximum above, this is +144.5 kWhm^{2}a^{-1}above mean target, and the non-PH outlier is close to five times greater than PH. Therefore, whilst some PH homes will use more energy than predicted, this is much less than for non-PH homes, and therefore the impact on energy use is much less and carbon reduction calculations can be made with greater confidence.

Two novel data collection adjustments were used to estimate space heating demand from total heat measurement. Adjustment 2 was applied to monthly heat meter readings and Adjustment 3 to biannual gas meter readings. These adjustments were then tested against known POE data. The difference between mean measured and mean estimated for Adjustment 2 was +0.03 $kWhm^2a^{-1}$ (SD1.9). The sample size was small (22 homes) and should be further tested against a larger data set, however for a simple and low-cost method to estimate space heating demand, this adjustment has the potential to be a useful tool. Whilst Adjustment 3 had a similar difference between mean estimated and measured data (-0.54 $kWhm^2a^{-1}$), SD was much greater (4.5 $kWhm^2a^{-1}$). This reflects the minimal data collected and variations in hot water use, which will affect the estimation of space heating. However, Adjustment 3 resulted in a small overestimation of space heating demand, which matched our cautious approach. Again, this method needs testing against a larger data set before any wider conclusions can be drawn, but as a very simplified method of data collection, an approximation of how a dwelling is performing in terms of space heating could be taken.

These results have two useful applications

1. The evidence shows the EPG is not prevalent in PH design in the UK. This has implications for future standards for domestic dwellings and is discussed further in this section.
2. Simple data collection methods, especially Adjustment 2, could be used to yield meaningful results. This would overcome some of the barriers to POE (cost and complexity).

These results come as the UK government is considering how new homes should look, through The Future Homes Standard (FHS). The UK needs to build many new low-energy homes, and those homes should not show an EPG. The developing FHS is giving the direction of travel for this (MHCLG, 2019), and the current consultation on the FHS has two options. Option 1 proposes a building fabric similar to PH but with the potential for natural ventilation, and Option 2 combines improved building fabric (but less stringent than Option 1 i.e. double rather than triple glazing), combined with low carbon technologies, with a current reliance on photovoltaics (PV) as a transition technology, until the grid further decarbonises.

Option 2 is the government's preferred choice, which depends on building services to deliver carbon emissions savings. POE has identified that integrating building fabric with technologies to meet higher buildings standards creates complexity. This complexity brings an increased risk of system failure and a lack of understanding of system controls (Pretlove and Kade, 2016). With Option 2, a failure of the PV system (or whichever technology is chosen) would mean a failure of compliance and an EPG. In addition, as shown, research into low-energy, but non-PH homes, identified a higher risk of the EPG, and this can be up to five-fold (Gupta et al., 2019).

As we move towards 2050 net zero carbon, new homes need to be as energy efficient as possible, so that the demand put on whichever technologies are employed is as small as possible, and a future upgrade to the building fabric avoided. This approach is more in line with the direction given by the CCC, where homes need not only to be low energy, but resilient to the future, including avoiding any costly retrofit (CCC, 2019). Looking at the fabric differences between Option 1 and Option 2, it would be sensible to specify the better standard now (Option 1) to avoid possible retrofit in the future, e.g. upgrading from double to triple glazing. This is a so-called ‘low-regret’ approach (CCC, 2019).

A further ‘low-regret’ action is air tightness. The main difference between FSH Option 1 and PH design is the absolute inclusion of air tightness and MVHR in PH. It has been argued that in a warmer maritime UK climate, adopting all the elements of the PH standard *except* very low air permeability and MVHR could be a viable option (Sassi, 2013). However, there is a direct link between non-airtight buildings and the EPG. Air movement and moisture through insulation materials could reduce their performance, especially in lightweight buildings (Kosiński et al., 2019). For example, POE show that air flow could reduce thermal resistance in external walls by 1–2% in an airtight construction, and up to 20% in a non-airtight construction (Thorsell and Bomberg, 2008). Roof U values also increased by up to 80% in a non-airtight construction (BBA, 2012). Therefore, there is risk that calculated U values, which may meet a quality control inspection, will not be delivered on-site, as a result of air movement, and the EPG will continue.

Air permeability in all new build homes has reduced to meet energy efficiency targets. There is a growing concern that this can lead to poor indoor air quality, not just in airtight but in naturally ventilated homes (McGill et al., 2015, Gupta and Kapsali, 2015). Air tightness itself does not automatically lead to inadequate ventilation rates, as small-scale studies have found good indoor air quality in homes using both approaches (Sassi, 2017). Indeed, installing MVHR has been associated with improving indoor air quality. CO_2 levels were found to be significantly lower in bedrooms with MVHR compared with naturally ventilated new homes (Colclough et al., 2018). However, this is not always the case, and PH homes have also been found to have poor indoor air quality (McGill et al., 2017a). A meta-analysis of MVHR in the UK found both improved indoor air quality and lower energy consumption when the MVHR was performing as intended, but poor design, installation, commissioning and maintenance, can lead to sub-optimal ventilation and therefore inadequate indoor air quality (Sharpe et al., 2016). MVHR is also linked to lower internal temperature (compared to naturally ventilated homes) and can stabilise internal temperatures, reducing the peaks (McGill et al., 2017b), which can help manage overheating.

MVHR is a relatively new technology to domestic homes in the UK. There will inevitably be a period of upskilling designers, installers, and occupants to ensure best use is made. Therefore, it may be that, once embedded and normalised as a ventilation strategy, the issues with indoor air quality will subside. As indoor air quality is not solely a PH issue, and naturally ventilated homes are showing similar issues, adequate ventilation is a concern for all new homes. As such, a review of Building Regulations governing ventilation, Part F, is also being undertaken within the FHS consultation (MHCLG, 2019).

The FHS is still under review. Option 1 contains elements which are linked to the EPG (natural ventilation), and Option 2 contains elements which may require retrofit at a later date (double vs triple glazed windows), as well as reliance on technologies which create complexity and risk failure. Our research shows that using the PH standard and investing in building fabric with quality assurance on-site, delivers new homes without the risk of the EPG and the need for future retrofit. Whilst it may be expensive but possible to replace windows, retrofitting air tightness and MVHR is much more complex and costly (White et al., 2016). As PH homes are constructed with both airtightness and triple glazing, this is a 'low-regret' option and should be considered for the FHS now.

At the start of the research, the three main causes of the EPG were identified as building modelling, construction, and user behaviour. The research in Chapter 3 showed that PH homes were not at risk of the EPG and that the impact of user behaviour on space heating demand could be minimised. These same three causes can be applied to the performance gap of overheating. The elements of high levels of insulation, air tightness and MVHR are not themselves a definitive cause of overheating. Rather, as UK housing moves towards being low energy, there needs to be a shift in design (managing solar gain, installing shading devices, cross ventilation), construction and commissioning (retaining solar shading, installation of MVHR, management of internal gains though building services) and user behaviour (opening windows, employing shading). This third element is shown to be critical. So, while PH homes can *design out* user behaviour on space heating demand, there is a need to *design in* user behaviour to manage overheating risk.

5.1 Future research

This thesis has demonstrated there is no evidence of the space heating EPG in UK homes constructed and certificated to the Passivhaus standard. Through conducting the work, areas for further research have been identified.

There is an increasing collection of research into low-energy homes, especially those constructed to meet a prescribed energy standard (Passivhaus, Code for Sustainable Homes, EcoHomes etc). What is missing is a comparable data set of homes constructed to standard building regulations. Certain attributes, increased risk of overheating or poor indoor air quality which have been attributed to highly insulated and airtight homes, may be the result of increased monitoring in this area only, and many more homes may be showing the same performance gap issues, but are unreported and therefore unrecognised, due to these lack of monitoring programmes. Therefore, more POE programmes of all new homes need to be undertaken to ensure all building designs and standards are performing as expected.

The simple data collection methods and adjustments used in Chapter 3 are one such low-cost approach, but further testing is needed against a larger data set, to ensure the accuracy of the method is sufficient to report the results with confidence.

When considering overheating risk, this research would be improved by comparing the temperature results with user experience. PHPP is based in a fixed upper internal temperature limit, whereas TM59, which is based on adaptive comfort, means that higher internal temperatures are tolerated in the risk assessment. Tolerance to these higher temperatures should be tested with occupants, to ensure they are within their thermal comfort ranges.

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